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## Geomorphic Evolution of Caminada Pass in Southeast Louisiana.

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Geomorphic Evolution of Caminada Pass in Southeast Louisiana.

A Thesis

Submitted to the Graduate Faculty of the  
University of New Orleans  
in partial fulfillment of the  
requirements for the degree of

Master of Science  
in  
Earth and Environmental Science  
Coastal Geology

by

Jordyn Spizale

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## Abstract

Tidal inlets play a significant role in barrier island sustainability along the barrier islands of southern Louisiana. With increasing tidal prism, major changes occur within and adjacent to the inlets. The purpose of this thesis is to examine how Caminada Pass, a tidal inlet along the Caminada-Moreau headland, has evolved through time. Fundamental to this effort is evaluating which processes have contributed toward inlet evolution and what is the response of the inlet-bordering barrier shorelines of Grand Isle and the Caminada Headland. This effort summarizes previous results and utilizes published bathymetric data, aerial photographs, vector shorelines, satellite images, and seafloor grab samples. The intent of this research is to document the variety of data that are available for future studies of Caminada Pass, an evaluation of long and short-term changes to the system, and an overall better understanding of the inlet dynamics of Caminada Pass.

Keywords: tidal inlet; barrier island; Lafourche Barrier Islands; Barataria tidal inlets; Louisiana coastal processes; sediment dynamics

## Introduction

Tidal inlets are passages that separate land regions such as barrier islands or mainland promontories. They provide a connection between the open ocean and interior backbarrier bays, marshes, and lagoons, with tidal currents acting to exchange water and sediment between the backbarrier environments and the open ocean. Tidal currents prevent channel closure by sand being transported alongshore (Escoffier, 1940). They have been shown to exert significant controls on local and regional shoreline dynamics along barrier islands shorelines across the world, but are mostly found most frequently along passive, micro-mesotidal continental margins that are backed by coastal plains (Inman and Nordstrom, 1971; Hayes, 1979; FitzGerald, 1996). Major controls on the morphology and characteristics of tidal inlets include: along shore and cross shore sediment supply, relative sea level changes, wave and tidal processes, tidal prism, tidal regime, basinal geometry, sedimentation history, storm impacts, and subsurface stratigraphic relationships (FitzGerald, 1996).

It has been suggested (Escoffier, 1940; Jarrett, 1976) that tidal prism or volume of water that is exchanged from the backbarrier to the ocean during half of the tidal cycle, is the most substantial influencing factor regarding the evolution of the tidal inlet. Importantly, the tidal prism of a coastal basin is not a static condition and can change through time, such as through the conversion of backbarrier land to open water, thereby affecting the geometry of the tidal inlet through which the tidal exchange is taking place (Jarrett, 1976). As Jarrett (1976) showed there is a direct relationship between the growth of a tidal prism and the growth of a corresponding inlet cross sectional area. An important function of tidal inlets is to transport sediment in a variety of vectors, from the backbarrier to the offshore, from the offshore to the backbarrier, and from adjacent, shore-parallel littoral cells. Part of the sediment that directly accumulates because of tidal inlet processes is stored in flood and ebb tidal deltas (FitzGerald, 1996). Sediment is transported

through the tidal inlet into the backbarrier during flooding tide forming a flood tidal delta, and it has been shown that along microtidal coast storms waves propagating inland through inlets contribute significantly toward this process (Hayes, 1975; Hayes, 1979; Walton and Adams, 1976; FitzGerald, 1996). During ebbing tide, sediment is transported from the backbarrier to the seaward side forming an accumulation of sediment, or ebb tidal delta that is subjected to subsequent modification by waves and tides. Ebb tidal deltas can represent significant reservoirs of sediment, characteristically in the same sand-size range, and substantially influence the distribution of wave energy and sand distribution along the adjacent shorelines (Hayes, 1975; Hayes, 1979; Walton and Adams, 1976; FitzGerald, 1996).

Along the south central Louisiana coast of the southern United States, there exists a number of tidal inlets separating barrier islands providing an excellent opportunity for study and ultimately further an understanding of tidal inlets in a sediment limited, microtidal environment that is subjected to rates of relative sea level rise that can locally approach 0.92cm/yr (Miner et al., 2009). The barriers, of the coastal zone, were formed by the marine reworking and dispersal from the deltaic headlands and the Mississippi River. The development of the barrier islands is closely linked to the delta switching model (Frazier, 1967; Penland et al., 1988; Penland and Boyd, 1988) such that once a deltaic headland is abandoned for another route, coastal processes, such as waves and longshore transport, move the sediment laterally to form barrier islands that front interdistributary bays. The bays behind the islands receive little sediment flux from surface runoff or riverine processes, but in the lower reaches of the bays, sand maybe transferred through the tidal inlets (Frazier, 1967).

### *Study Area*

The focus of this project is Caminada Pass, which is a tidal inlet that separates Grand Isle from the eastern end of the Caminada-Moreau headland at Elmer's Island (Fig. 1). Grand Isle was

formed by updrift longshore transport of sediment eroded from The Bayou Lafourche headland and transported toward the east. The headland formed from the abandonment of the Lafourche Delta lobe approximately 300 yrs BP (Frazier, 1967). This process resulted in downdrift spit accretion that was later breached at Caminada (Penland, 1988). Grand Isle is located to the east of Caminada Pass where this is a 800m rock jetty that extends out into the Gulf of Mexico. The construction of the rock jetty was completed in July 1972 to stop critical erosion occurring in this area (U.S. Army Corps of Engineers, 1979). Elmer's Island, a National Wildlife Reserve, is located to the west of the pass. There is a unique recurved spit that is 2502.3m in length that protrudes from Elmer's Island toward the back of Caminada Pass into Caminada Bay. A recent bathymetric analysis conducted in 2007 indicates the inlet to be approximately 400m wide and 12m deep at the inlet throat (FitzGerald et al., 2007). The cross sectional area of the inlet was 809m<sup>2</sup> in 1880 (FitzGerald et al., 2007), whereas, the cross sectional area of the inlet is 3,372 m<sup>2</sup> as of 2006(FitzGerald et al., 2007). This change in cross sectional area represents a 4-fold increase within the 126 years.

### *Purpose*

The focus of this study is Caminada Pass, a tidal inlet separating the Caminada-Moreau headland and the flanking barrier island Grand Isle. The primary purpose is to give a historical account of Caminada Pass during the past 130 years. The study will focus on the evolution of the inlet channel and ebb tidal delta, as well as what processes govern these changes.

This barrier shoreline is recognized to be an example of stage 1 within the 3-stage evolutionary Penland (1988) model, and was formed by the abandoned Lafourche delta lobe that was in existence approximately 1000-300 years BP (Frazier 1967). Caminada Pass, similar to the adjacent barrier islands, has been subjected to a reduced sediment supply, coastal processes such as tides and waves, and changes in tidal prism; collectively all of these have attributed to its present form of the inlet. Caminada Pass and the adjacent shorelines have been affected by long term and

short-term impacts from coastal processes. Long-term impacts include wetland deterioration due to relative sea level rise and subsidence. Short-term impacts include impacts from hurricanes and cold fronts.

### *Key Questions and Hypothesis*

Tidal inlets along the south-Central Louisiana coastline are a focus of research because coastal zone management requires a better understanding of the fundamental processes controlling their formation, distribution, and sedimentary framework (Levin, 1993) and the overall morphology (FitzGerald et al., 2004). In contrast to other inlets of the central Louisiana coastal zone, (e.g. Levin, 1993, FitzGerald et al., 2004) Caminada Pass has not been studied in detail and little information exists regarding its overall evolution. Similar to other south-central Louisiana coast inlets, there have been changes to its cross sectional area, lateral migration, size and volume of its ebb and flood tidal deltas. Moreover, Caminada Pass separates Grand Isle, the only developed barrier island on Louisiana's Coast from the Caminada Headland. Understanding Caminada Pass's evolution is vital to the survival of these barrier islands.

Some key questions that are to be addressed by this research:

1. What has been the geomorphic framework of Caminada Pass's evolution between the 1880s and 2012? Specifically, how has the inlet expanded in width or depth and are there any specific changes to the inlet geometry that are a result of nearby natural or anthropogenic shoreline alterations.
2. Have the dynamics of the historic changes of Caminada Pass had any specific influences on the ebb and flood tidal deltas?

3. What is the source of sand that, within approximately the last decade, that contributed to the growth of the recurved spit on the bayside of the inlet near its entrance to Barataria Bay?
4. What coastal processes including shoreline modifications are controlling or altering the sediment budget of the inlet and the adjacent shoreline?

A fundamental component of this research is the well-established relationship between tidal prism and cross-sectional size of tidal inlets. Tidal prism is defined as the volume of water entering and exiting an inlet during flood and ebb tide respectively (Escoffier, 1940; Jarrett, 1976). With increasing tidal prism, inlets naturally respond by either widening and/or deepening (Jarrett, 1976). With the conversion of land to open water in Caminada and Barataria Bay has caused a net increase in the tidal prism through the inlet. Similar to other tidal inlets in Louisiana, Caminada Pass has shown progressive increase in size and an increase in cross sectional-area. These increases have led to sand being sequestered in ebb tidal delta and its simultaneous increase in size (Miner et al., 2009).



Figure 1: Satellite image of Caminada Pass in 2001 (source: ESRI world imagery). Caminada Pass is located east of the Caminada-Moreau Headland and west of Grand Isle. Caminada Bay lies to the north of Caminada Pass and the Gulf of Mexico lies to the south.

## Background

### *Formation of the Mississippi River Delta Plain*

The formation of the deltaic plain and barrier islands off the coast of Louisiana is fundamentally linked to the Mississippi River. Since the late Wisconsin sea level lowstand, the Mississippi river has been transporting sediment to the north-central Gulf of Mexico coast through a geographically and chronologically diverse suite of distributaries. These distributaries have created delta lobes, which in turn have collectively coalesced to create a series of delta complexes and in turn the delta plain (Robert, 1994). It is widely recognized that there are essentially six major delta complexes that have formed during the last 7000 years (Frazier, 1967). These includes from oldest to youngest: the Maringouin (~7,500-5000yrs BP), Teche (5500-3800 yrs. BP), St. Bernard (~4000-2000 yrs. BP), Lafourche (~2,500-800 yrs. BP), and Plaquemines-Balize (~1,000 yrs. - present), and Atchafalaya (~400yrs-present) (Törnqvist et al., 1996; Robert, 1997). Figure 2 is a map of the six different delta complexes, as well as the barrier island systems that currently front each of the complexes. The presences of flooding surfaces, ravinements, and facies successions, have all been used to identify separate delta complexes within the larger delta plain. Individual delta complexes stratigraphically overlap as a response to the evolutionary cycle of delta progradation, overextension, and abandonment (Roberts, 1997). A conceptual model of how the different delta lobes become stratigraphically stacked is presented in figure 3.



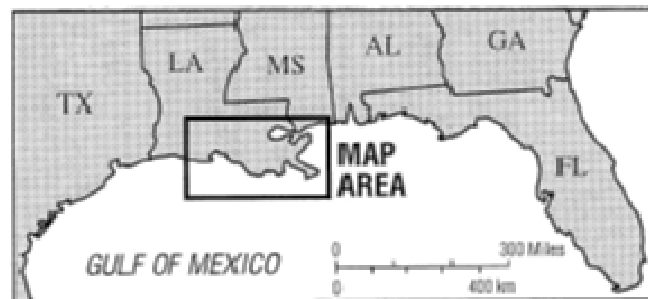
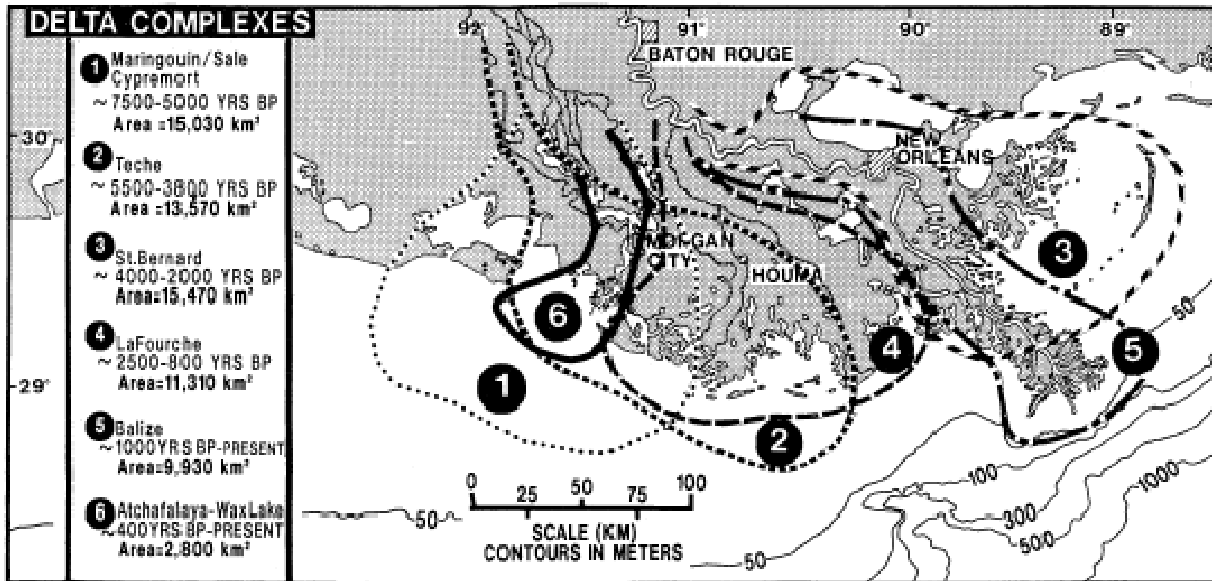


Figure 2: Map showing the distribution and timing of abandoned and currently active delta complexes of the Mississippi River (Roberts, 1997). The Maringouin, Teche, St. Bernard, and Lafourche are the abandoned delta complexes. The Balize and Atchafalaya are the active delta complexes.

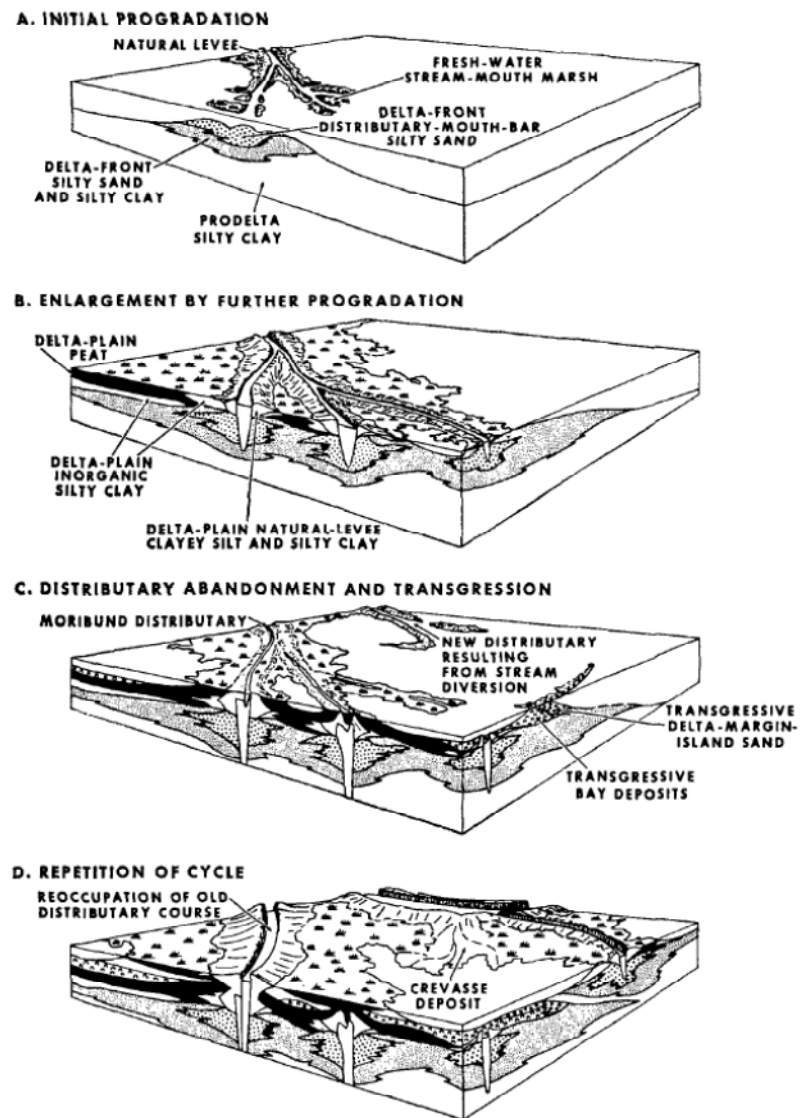


Figure 3: Conceptual model for the deltaic deposits built during distributary progradation and the barrier island systems created from abandoned distributaries. When a river reaches a standing body of water, a delta is formed and progradation of the delta occurs. Through time, a river may change its course if the current course is no longer feasible and easy to reach. Abandonment of the course will then follow. The subsurface of this diagram displays the older distributary packages overlain by the newer ones (Frazier, 1967).

### *Regressive and Transgressive Phases of the Mississippi River*

The Mississippi River delta cycle has two major phases: components of growth and decay, which have been referred to as a regressive phase and transgressive phase, respectfully. A delta

cycle begins once a delta lobe-switching event is initiated (Roberts, 1997). The regressive phase has been studied in greater detail along the coast, because sediment depositions from delta progradation have contributed to the current morphology of the coastline, but it is however, the transgressive phase that has been the major contributing factor for the greater part of the Holocene. The reason is because transgressive sedimentation can provide as much as 50% of the total thickness of a deltaic sequence (Penland et al, 1988).

The regressive phase of deltaic evolution involves the progradation of the coastline toward and eventually onto the continental shelf because of seaward advancing distributaries. If the progradation continues for a long enough period of time and there is ample sediment supply, the process results in the construction and progradation of the deltaic front. Coarsening-upward deposits are evident in the stratigraphic record of progradation, as fluvial deposits prograde outward over mud-rich strata typical of the prodelta platform and the continental shelf (Kolb and van Iobik, 1958; Frazier, 1967; Roberts, 1997; Coleman et al., 1998; Kulp et al., 2005b). Across the Mississippi Delta plain the only areas currently undergoing substantial regression as a result of progradation are the Balize bird's foot delta (and only locally) and the Atchafalaya-Wax Lake system to the west (Robert, 1997).

Progradation leads eventually to an overextension of distributaries, and as a result, stream diversion into a steeper gradient course will take place (Frazier, 1967). The transgressive phase of the delta cycle becomes dominant after a delta abandons its course for a different route, and marine processes and subsidence now have a larger effect on the limited sediment supply (Roberts, 1997). Erosional headland retreat and landward migration of the shoreline is the direct result of this shift to the transgressive phase. An erosional headland is formed from the abandoned delta lobe that is reworked by marine processes, and sediment will be also be dispersed laterally from the center, and transported to the flanks to form recurved spits (Penland and Boyd, 1985; Penland et al. 1988).

The stratigraphy is represented by a sequence of lagoonal muds, barrier sand bodies, sand shoals, and organic deposits (Kulp et al, 2005). An example of the delta cycle is provided in figure 4.

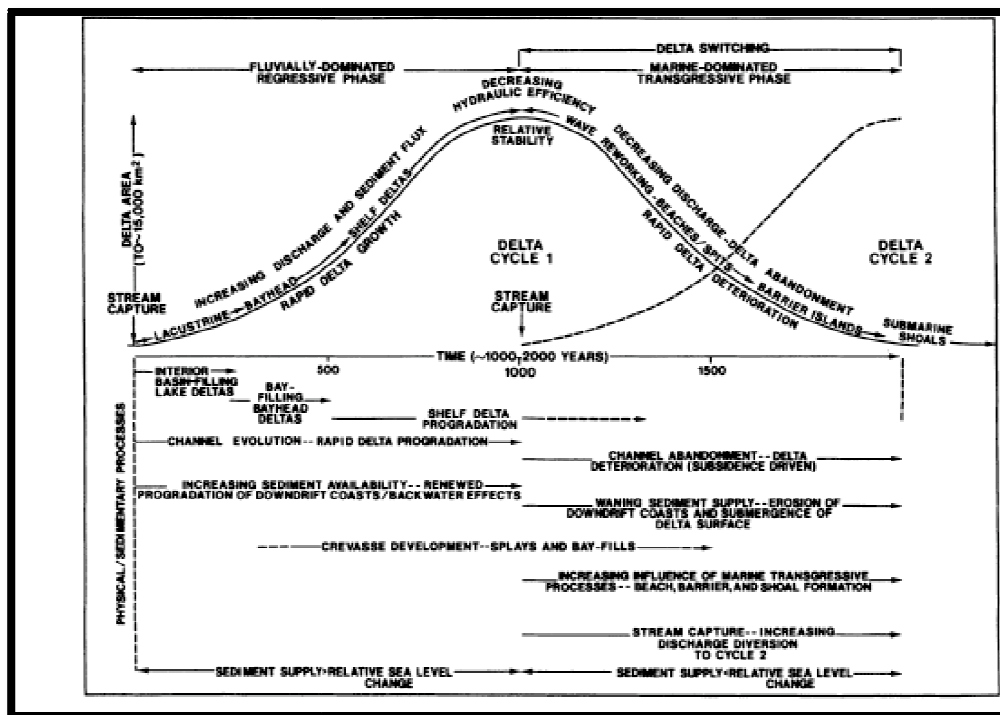


Figure 4: A diagram illustrating the regressive/ transgressive phases of the delta cycle (Penland et al., 1988; Roberts, 1997). The top half of the figure displays time versus delta area during each of the two phases. The bottom half of the figure provides an indication of the sedimentary responses associated with each phase of evolution.

### *Louisiana Coastal Processes*

The Gulf of Mexico is classified as a storm dominated environment due to frequent cold fronts and hurricanes, a micro-tidal setting, and small to moderate wave energy (Penland and Suter, 1988; Georgiou et al., 2005). Some of the physical processes that affect the southeast barrier islands include: wave climate, storms, longshore sediment transport, cross-shore sediment dispersal, tides, relative sea level rise, and tidal prism dynamics (Georgiou et al., 2005).

### *Wave Climate*

The average annual wave heights are as low at 0.75m of the central Louisiana coast at station 42017 (Georgiou et al., 2005) and as high as 0.95m offshore of both Holly Beach (Station GCBL1) and Head of Passes (Station LNEL1)(Georgiou et al., 2005), and dominantly approach the Louisiana coast from the southeast. Mean annual wave periods range from 4.5 to 5.9 seconds. The longest average period is recorded off Holly Beach (Station GCBL1) and the shortest average period is recorded at the northern Chandeleur Islands location (Station 42007)(Georgiou et al., 2005).

### *Tides*

Tides have a mean range of 0.37m and are diurnal (Penland and Suter, 1988; Georgiou et al., 2005). The wave climate includes both deep water waves and nearshore waves, and they are a product of seasonal wind patterns and tropical and extratropical storms (Georgiou et al., 2005). Depending on the season and type of storm will dictate the wave size and direction propagation. From mid-spring to mid-fall, winds are predominantly from the south to southwest, and waves approach from the southwesterly quadrant. From late fall to early spring, winds frequently blow from the northeast as cold fronts extend across North America and into the northern Gulf of Mexico. However, the waves approach predominantly from the southeast and therefore control sediment transport. (Georgiou et al., 2005)

### *Longshore patterns*

Longshore transport processes play a fundamental role in the rapid erosion and translation of the islands (List et al., 1997). Shoreline change analyses, sedimentation patterns and numerical wave refraction modeling are the main ways in which longshore sediment transport rates can be assessed (Georgiou et al., 2005). Deltaic sands that have been reworked by waves provide the sediment to the longshore transport system of the Louisiana barrier islands. Midway along the

Caminada-Moreau headland there is a drift divide that results in opposing sediment transport vectors: 146, 000 m<sup>3</sup>/y moves eastward along Grand Isle, and 11,000 m<sup>3</sup>/yr moves westward toward Terrebonne Bay (Georgiou et al., 2005).

### *Cross-shore Patterns*

Sediment that is eroded from the headland and transported to an offshore location or transported onshore by overwash processes is considered cross shore sediment dispersal. Evidence for cross shore transport is recognized along the Louisiana coastal barrier systems in the form of extensive subaerial overwash fans and intertidal to subtidal overwash platforms, which are present along the backbarrier. Offshore sediment dispersal and redistribution is observed in bathymetric area change maps for the areas located seaward of the Bayou Lafourche shoreline (Fig. 5) because they track net sediment movements (Miner et al., 2009). There has been large-scale erosion in this area, which likely has contributed to some of the cross shore dispersal. Erosional patterns extend offshore to the 15m isobath, however the most substantial erosion (>2.5m) has taken place proximal to the shoreline (Georgiou et al., 2005). Vertical accretion (>2.5m) in this area can be seen along the Barataria and Terrebonne bay embayments (Georgiou et al., 2005).

The mechanisms of cross shore processes are not very well understood, but it has been suggested that the rates of accretion and erosion trends suggest that sediment is transported from the headlands to the embayments (Georgiou et al., 2005). Some of this storm-induced erosion is thought to be transported alongshore and is passed through the tidal delta complex as opposed to being stored in an offshore bar. This is evident of the small amount of sediment that returns to the beaches following a storm despite the fact that offshore bar fronts most of the coastline (Harper, 1977).



beach berm, overwashing of low barriers; increased tidal exchange that can enlarge existing tidal inlets; and short-period backbarrier waves, due to northerly winds, in the bays that cause chronic shoreline erosion along the bay side (Stone et al., 2004).

### *Tropical Cyclones*

Hurricanes contribute to the long-term morphologic evolution of the coastline as much as limited sediment supply, eustatic sea-level rise and subsidence (Stone et al., 1997). Estimates suggest that storms contribute as much as 90% of the long-term erosion trends in Louisiana (Stone et al., 1997). More than thirty-five hurricanes have been known to have caused significant damage to the Louisiana coast since records first started in 1722 (Stone et al., 1997). The severity of a tropical cyclone impact is governed by strength, speed, and size of the storm. Wind velocity is a major factor in the degree of erosion and the amount of damage (Georgiou et al., 2005). It also constitutes the extent of the storm surge. Wind velocity and wave energy have a direct correlation; the higher the wind velocity, the larger the waves (Stone et al., 2004.) Of all the factors affecting the coastline, hurricanes, however, have the most significant, short-period impact on barrier islands and cause erosion, elevation reduction, washover channels, breaches, sediment transport and fragmentation (Nummedal et al., 1980)

### *Formation of the Mississippi River Delta Plain Barrier Islands*

The formation Mississippi River Delta barrier islands, as a result of delta lobe abandonment and relative sea level rise (RSL), is depicted in three-stage conceptual model proposed by Penland (1988; fig. 6). The first stage of the cycle is an erosional headland that represents the land built after the river has diverted to another course. This phase is characterized by flanking barrier islands that form by sand that is eroded from the headland and transported alongshore to the flanks. Tidal inlets separate the mainland from the flanking barrier islands. The second stage in the evolutionary



model involves the formation of a barrier island arc that formed by detachment of the barrier shoreline from the mainland. The final stage is the inner-shelf shoal formed once the barrier island has undergone transgressive submergence. It is proposed that all three stages of this model are currently in existence along the periphery of the Mississippi River delta plain with the Caminada-Moreau Headland representing stage 1, the Chandelier Islands representing stage 2, and Ship Shoal representing stage 3 (Penland et al., 1988).

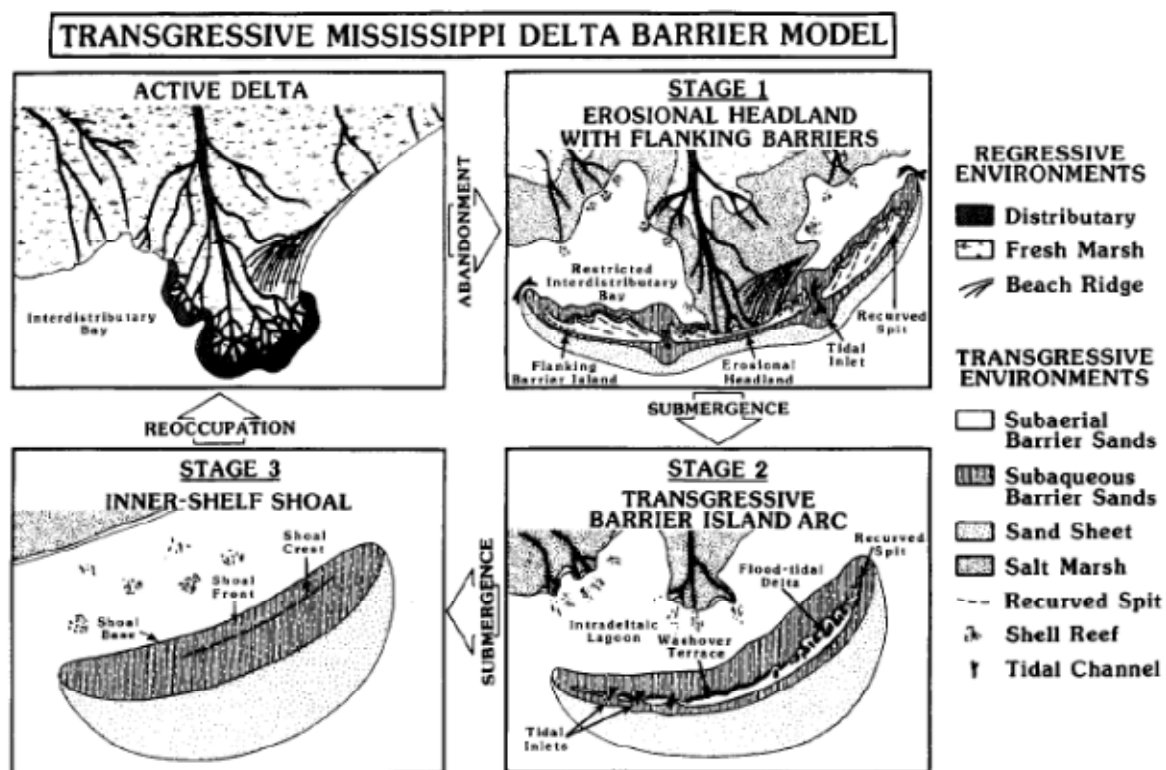


Figure 6: Sequential model showing the genesis and evolution of the Mississippi River deltaic barrier islands during a transgression. (Penland et al., 1988) After the delta abandons its current course cutting off sediment supply, the remaining sediment is reworked laterally by marine processes marking the beginning of stage 1. Stage 1 is characterized by an erosional headland with flanking barriers separated by tidal inlets. RSLR and impact from storms will result in an increase of the backbarrier being converted to open water. Eventually, a barrier island arc will form as a result of a less restricted bay area and barrier detachment forming stage 2 of the model. Stage 3 develops due to high rates of RSLR and a depleted sediment supply causing the barrier islands to be submerged underwater forming a transgressive marine uniform sand body or sand shoal.

### *The Bayou Lafourche Barrier Islands*

The study area is located within the abandoned Bayou Lafourche delta complex (Fig. 7), which represent a south-central section of the Mississippi Delta Plain Barrier Islands. The formation of this barrier island chain is an example of a stage one barrier within the evolutionary 3-stage model proposed by Penland (1988). The Lafourche system was the last known active delta complex before the Mississippi river moved to its present day location at the Balize delta (Frazier, 1967). The primary sources of sediment are from the Bayou Lafourche distributaries and Cheniere Caminada beach ridge plain (Kulp et al., 2005b; Gerdes 1985). The stratigraphy, as depicted in cross section (Fig. 8), of the Bayou Lafourche barriers consist of an eroding shoreface, distributary, and beach-ridge sand bodies overlying a sequence of regressive deltaic muds (Penland et al., 1988).

Currently, the barrier islands of the Lafourche delta complex are migrating landward due to the combined effects of eustatic rates of sea level rise, limited sediment supply, and subsidence along the coast. Collectively, eustatic sea level rise and subsidence have caused the highest rates of relative sea level rise in the Gulf of Mexico Basin and the nation (Penland et al, 1989; Penland and Ramsey, 1990). Current rates range from NOAA tide gauge 9.24 +/- 0.59mm/yr for the time period of 1947-2006 at Grand Isle. The Lafourche deltaic shoreline is undergoing an average historical coastal shoreline retreat of -7.50m/yr (1855-2005). The long-term coastal shoreline retreat is averaged at -6.1 m/yr (1905-2005). The short-term coastal shoreline retreat is averaged at -8.0m/yr (1996-2005) (Martinez et al., 2009). At this current rate of erosion, 1,100km<sup>2</sup> of wetlands have been converted to open water since 1935 in Barataria Bay (Fitzgerald et al., 2007; derived from Britsch and Dunbar, 1993; and Barras et al., 1994, 2003). It has been predicted that Louisiana's interior wetlands and marshes will continue to be converted to open water losing an additional 4,000km<sup>2</sup> during the next half century and ultimately lead to barrier disintegration if nothing is done to stop erosion (Boesch et al., 1994; Stone and McBride, 1998).

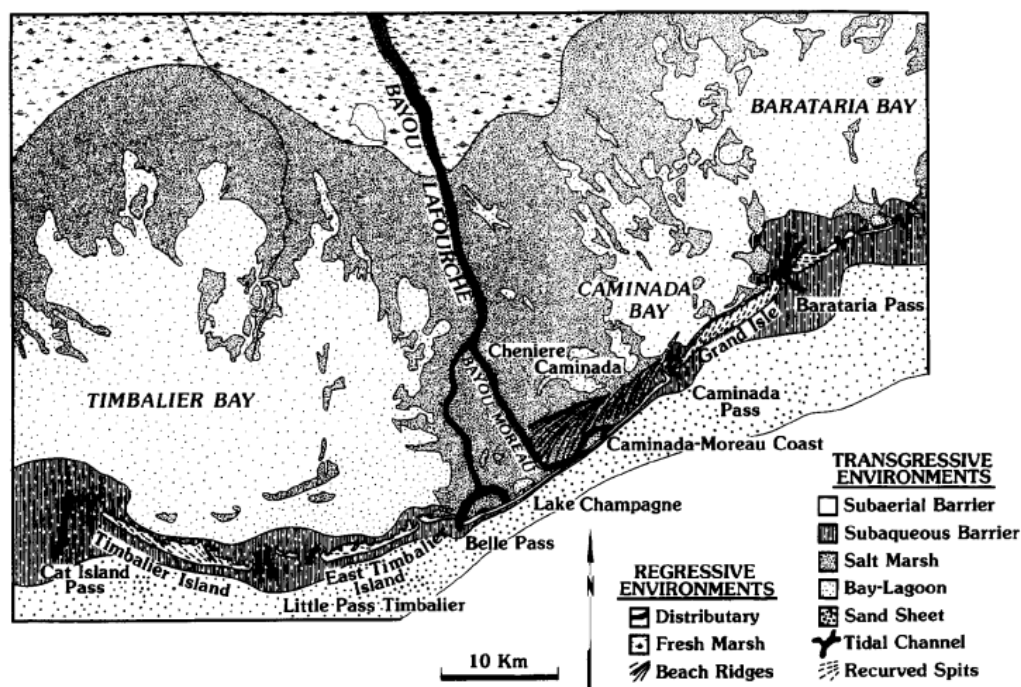


Figure 7: Map of the Lafourche Barrier system displaying the locations of the Caminada-Moreau headland and the adjacent barriers formed from the reworking of sediment from the headland to the flanks (Penland et al., 1988).

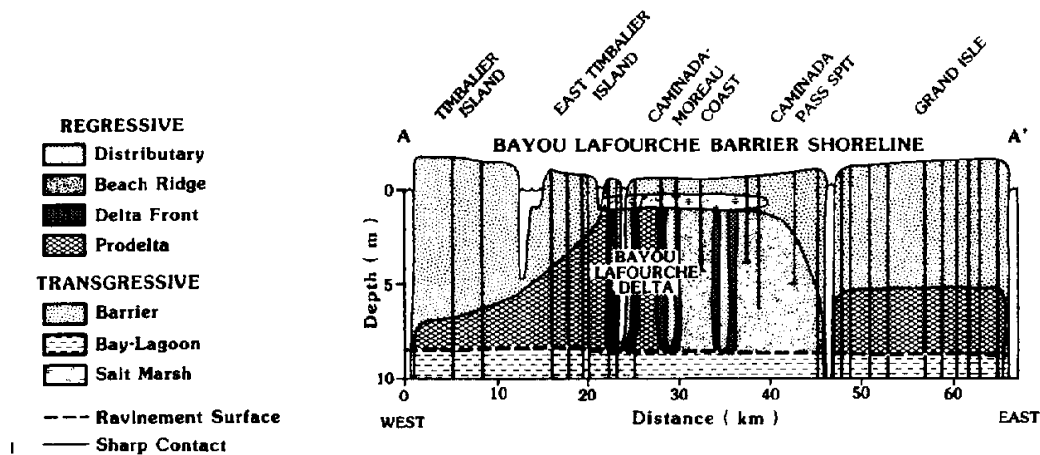


Figure 8: This figure is a cross section trending through the Lafourche Barriers showing stratigraphy and sedimentary features. The cross section displays the transgressive/regressive facies relationships of the Bayou Lafourche delta. The sand bodies thicken downdrift toward Grand Isle, which is indicative of longshore transport toward the eastern flanks of Grand Isle (Penland et al., 1988).

## *Tidal Inlet Formation*

Tidal inlets are created during hurricanes and other storm events when barriers are breached during overwash processes. If tidal exchange through the breach is strong enough to overwhelm breach closure processes created by longshore transport then these tidal inlets can maintain a permanent tidal exchange that leads to the generation of ebb and flood tidal deltas (Boyd and Penland, 1988). A four-stage conceptual model (Fig. 9) for inlet formation and evolution on the Louisiana coast was proposed by FitzGerald (2004): Stage 1) The growth of a tidal inlet on a barrier island begins with a pre-inlet morphology that is characterized by a continuous barrier island with no tidal inlets; Stage 2) called the incipient inlet, involves the breaching of a barrier due to overwash forming a small tidal inlet and a poorly developed ebb-tidal delta; Stage 3) An increasing tidal prism causes stage three to form a mid-stage inlet, and this stage creates a moderate size inlet with an ebb-tidal delta that extends 1-2km offshore; Stage 4) The transition from mid-size to mature involves the transport of sand offshore across the ebb-tidal delta covering finer grained muds of the distal ebb-tidal deltas. Stage 5) the final stage, called the deteriorating barrier stage, occurs when most of the wetland areas have been created to open water causing an increase in tidal prism. This eventually forces the adjacent barriers to thin and fragment creating new tidal inlets. Tidal flow, within the former larger tidal inlets, decrease due to the dispersal of bay tidal prism and increase of tidal inlets. Ebb tidal deltas facies are overlain by mud facies from the inner shelf (FitzGerald, 2004).

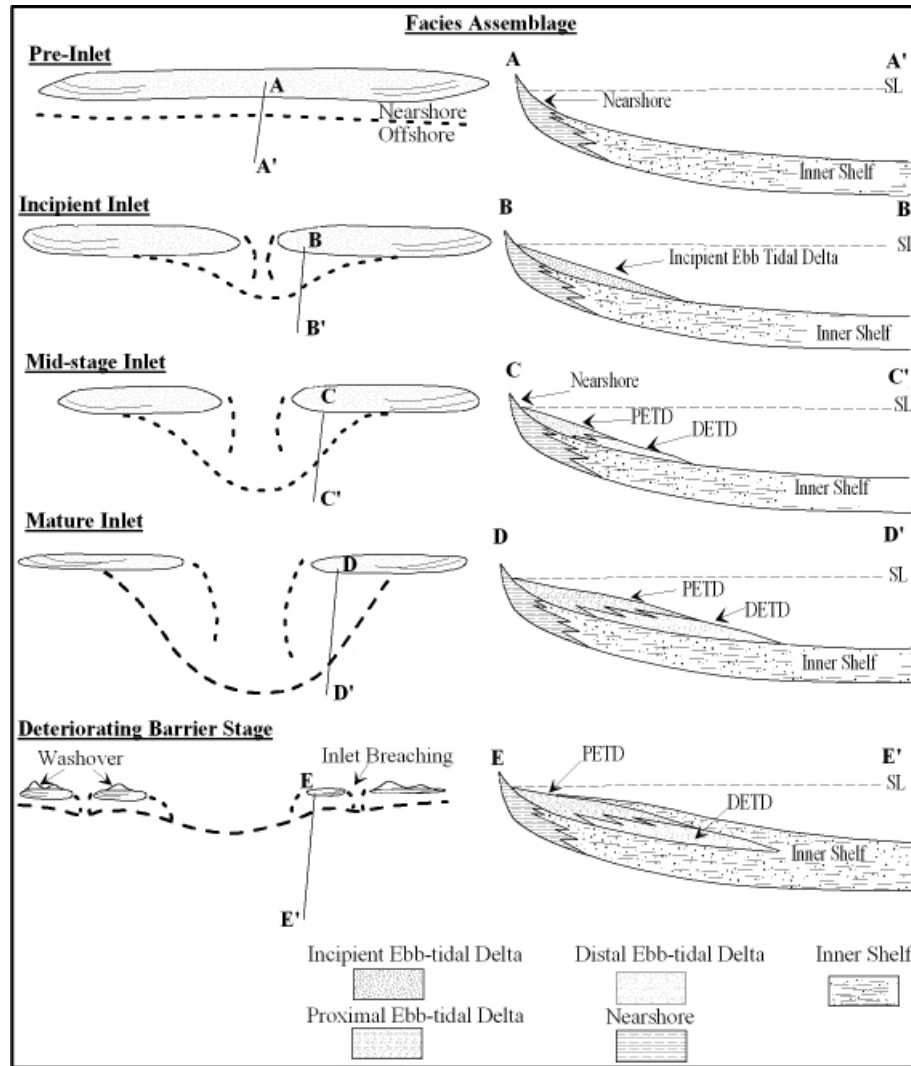


Figure 9: Figure illustrating the five stage conceptual model of a tidal inlet. The stages include: 1) pre-inlet, 2) Incipient inlet, 3) Mid-stage inlet, 4) mature inlet, 5) Deteriorating barrier stage. One of the main components of this conceptual model is the evolutionary growth of the ebb tidal delta through each stage; from non-existent to ebb tidal growth enlargement, too much of the ebb-tidal delta deposits are no longer accessible because they are covered in mud (FitzGerald et al., 2004).

### *The Barataria Tidal Inlets*

The Barataria Barrier Islands and their associated tidal inlets are undergoing rapid morphological change driven by inlet response to tidal prism increase. The island chain consists of Grand Isle and Grand Terre (List et al., 1994). High rates of relative sea level rise ( $9.27 \pm .34$  mm

yr<sup>-1</sup>; Kolker, et al., 2011), sediment starvation, and the impacts of tropical cyclones result in interior areas behind the inlets converting into open water. This in turn increases the volume of water through the tidal inlets, and causes an increase in inlet cross sectional area through either inlet widening and/or deepening (Escoffier, 1940; Jarrett, 1967; Walton and Adams, 1976). The size of the tidal prism determines how much sand can be lost from the intertidal to supratidal barrier system and transported offshore to be stored in ebb tidal deltas (FitzGerald et al., 2004; List et al., 1997).

The evolutionary stages of tidal inlets are observable along the Barataria Bay barrier island chain (Fig. 10). Sequential bathymetric and shoreline maps from 1880 to 1980 document the development of tidal inlets in the Barataria region. The 1880s map displays the shoreline with relatively wide long barriers, and small tidal inlets. For example, at that time it is indicated that Caminada, and Quatre Bayou passes were less than 200m wide and less than 5m deep at their throats (FitzGerald et al., 2004). Grand Isle and Grand Terre continued to deteriorate, and by the 1930's, their tidal prisms grew due to the deterioration of wetlands converting to open water in Barataria Bay. The greater volume of water resulted in a breach in Grand Terre forming Pass Abel, and an increase in size at Caminada and Quatre Bayou passes. By the 1980's, large parts of the islands have disintegrated as tidal inlets widened and deepened and the tidal prism increased. The outcome of these changes to tidal prism resulted in the widening of Pass Abel, Caminada Pass, and Quatre Bayou at the expense of the adjacent barrier islands (Grand Isle and the Grand Terre Islands). The cross-sectional area of Pass Abel, Caminada Pass and Quatre Bayou quadrupled in size since the 1980's resulting in a cross sectional area of 4193m<sup>2</sup>, 1532m<sup>2</sup>, and 3777m<sup>2</sup>, respectively (FitzGerald et al., 2004; Fig. 11).

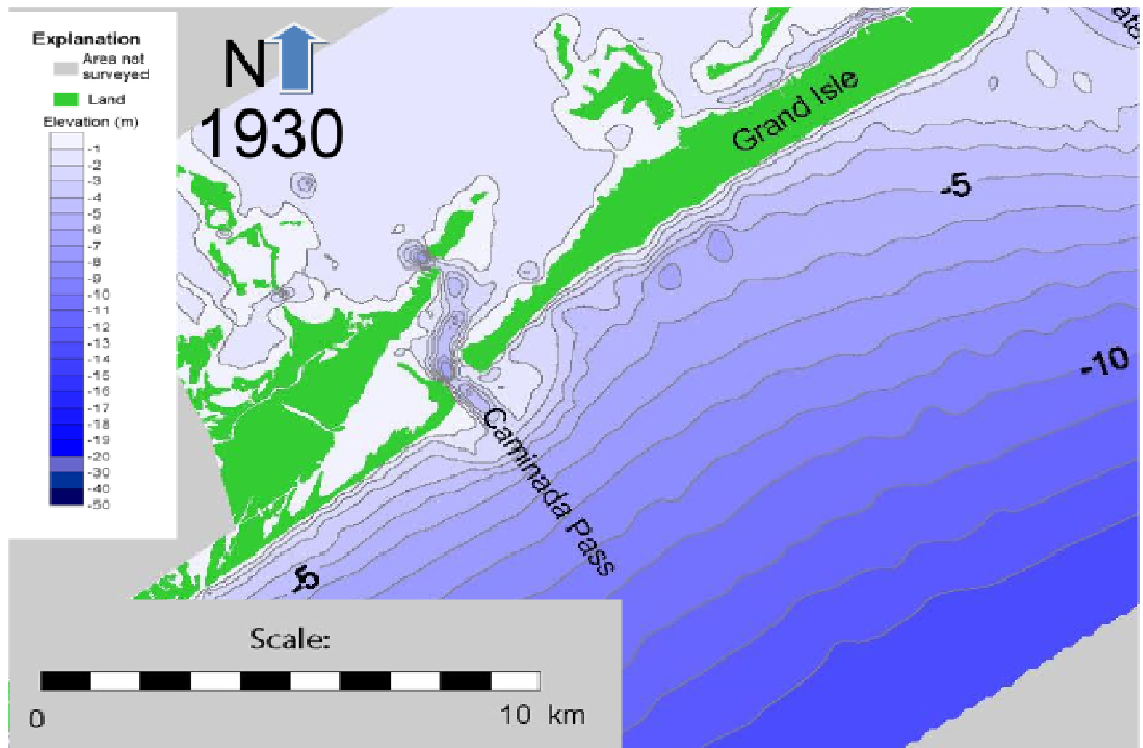
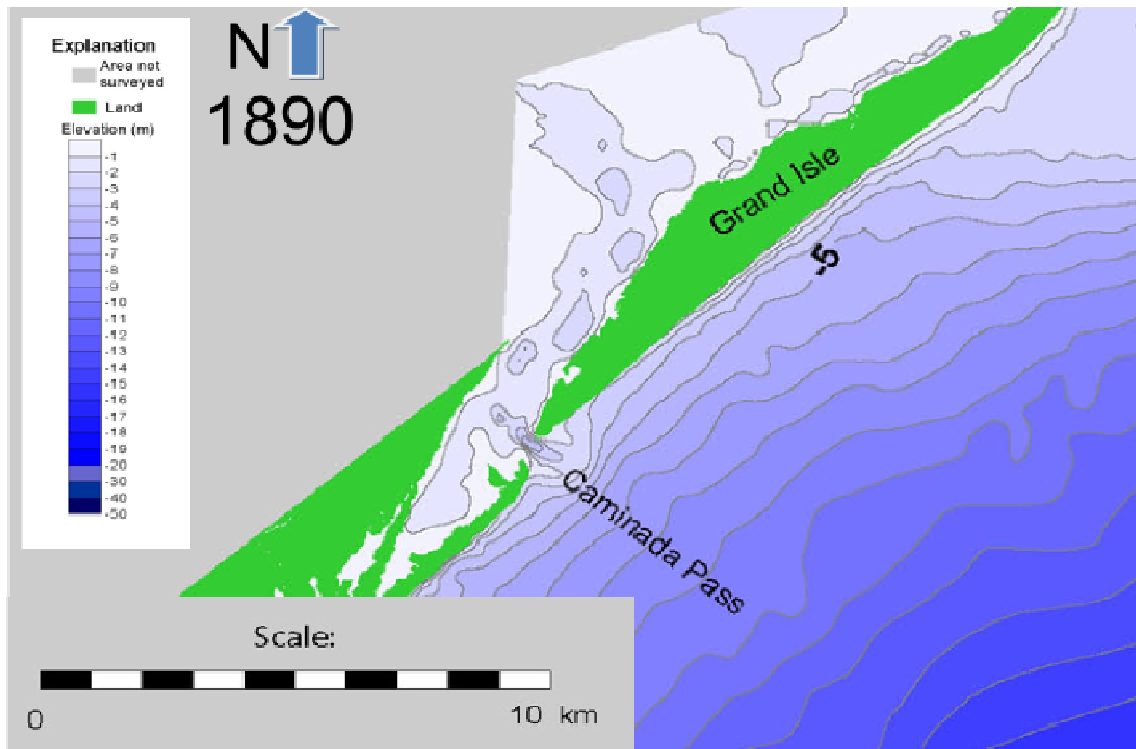


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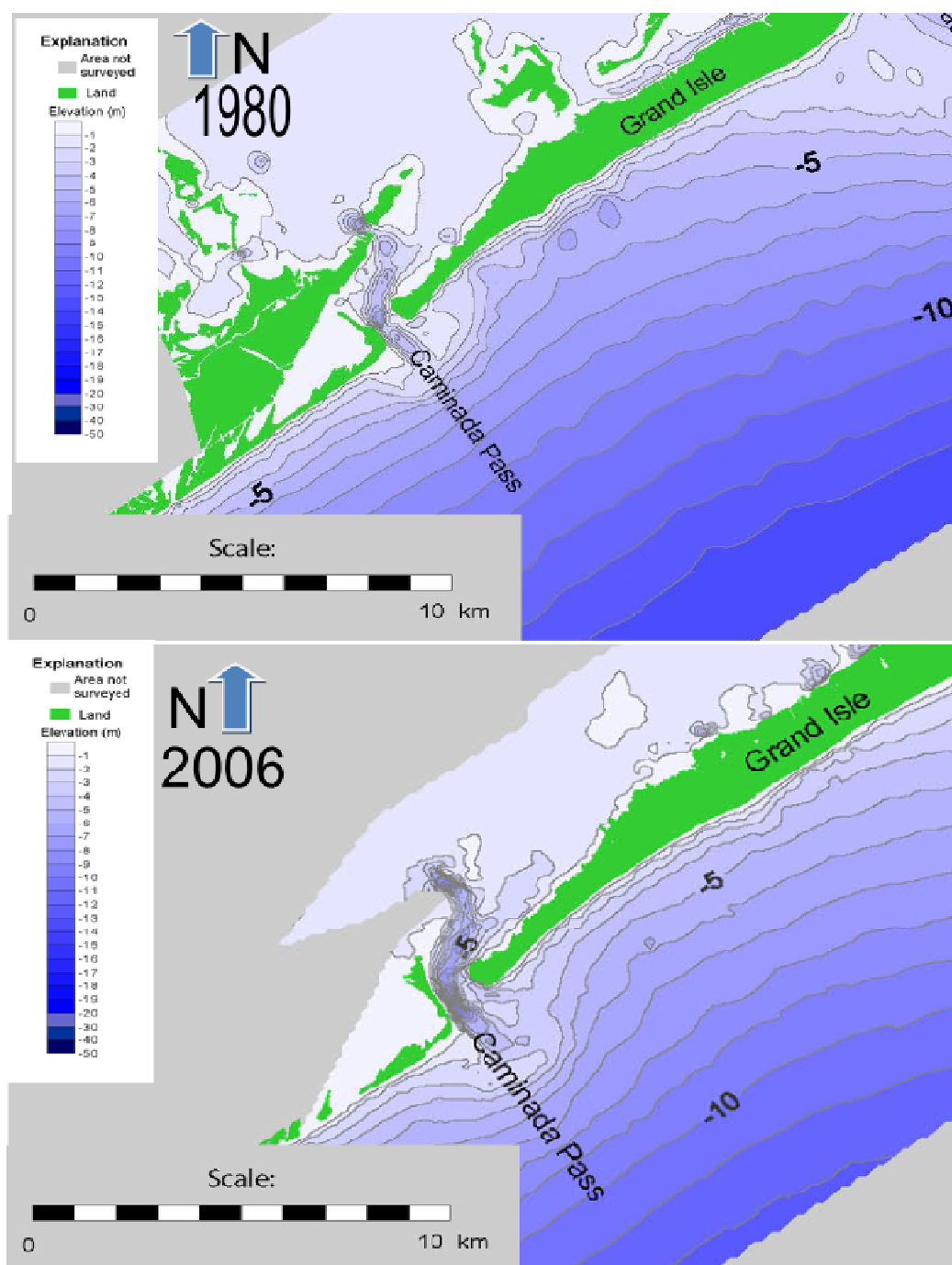


Figure 10: Bathymetric map displaying the morphologic evolution of the central Louisiana coastal plain barrier islands and their tidal inlets from 1880-2006. The result of an increase in Barataria Bay open water is reflected in widening and deepening inlets of Barataria Pass (BP), Caminada Pass (CP and the one circled in red), and Quatre Bayou Pass (QBP) and the formation of Pass Abel (PA) (modified from List et al., 1994 and hydrographic surveys conducted by UNO-PIES).



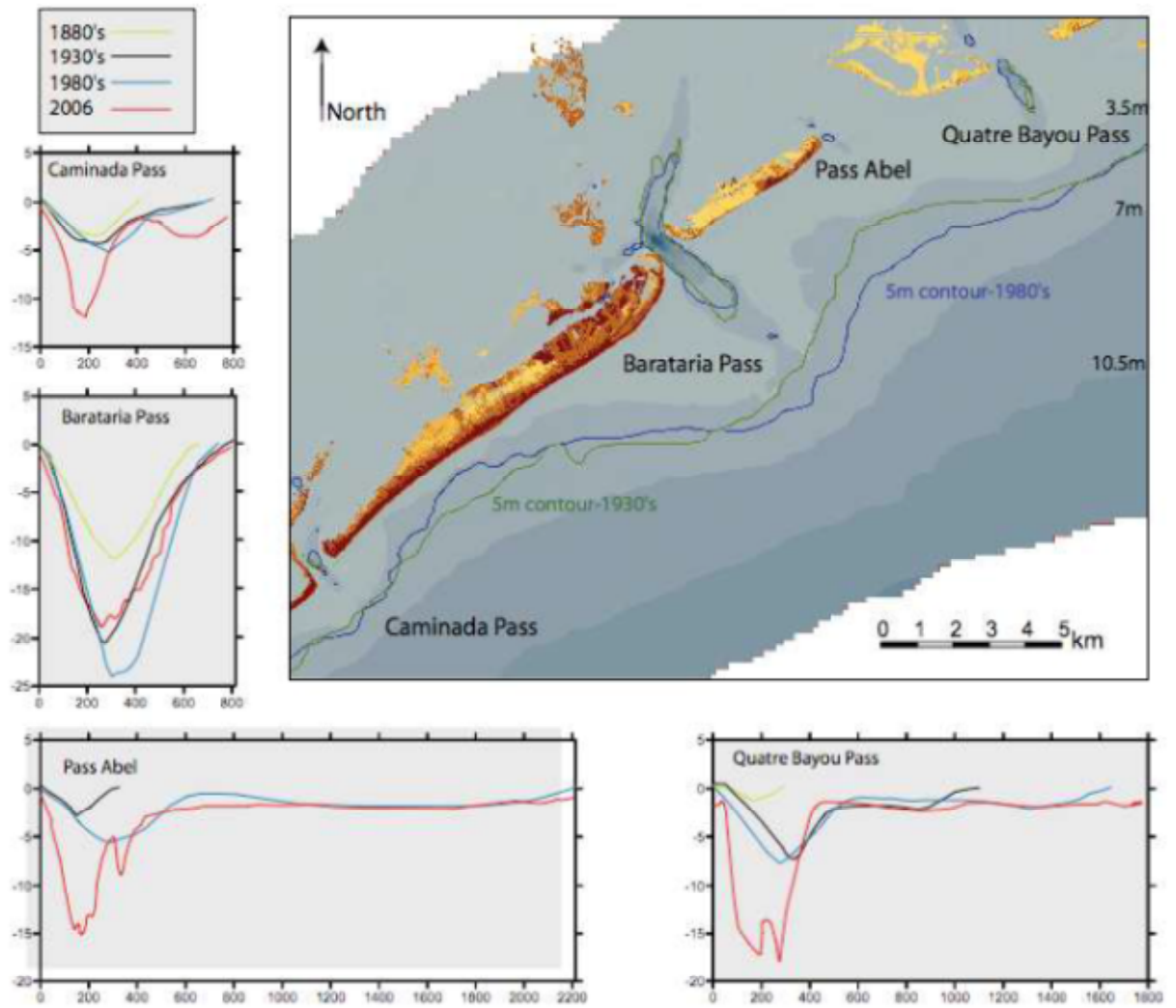


Figure 11: Shore-parallel profile showing the changes in cross sectional area of the central Louisiana coastal plain tidal inlets for the time periods 1880, 1930, and 1980 ( from FitzGerald et al.,2007,data from List et al., 1994).

## Methods

The methods of this research were designed to test the hypothesis of the study and to additionally address research questions stated previously. The goal of this research is to examine how Caminada Pass has evolved by examining its sedimentology and geomorphology. Historical data sets, from the Barrier Island Comprehensive Monitoring (BICM), oblique aerial photography, and Landsat satellite images are collectively used to document shoreline changes between reference datasets from the 1880s, 1930's, 1980's, and 2006 (Fig. 12). These data sets were employed from previous work done by others. BICM is a program that was developed to document the long-term morphologic changes and characteristics of the Louisiana coastline. The program was created to address questions posed in this project and effectively identify the magnitude, rates, and processes of sandy barrier shoreline changes along Louisiana. These data sets are composited with the use of Geographic Information Software Systems (GIS) modeling to create maps that display sediment transport trends and shoreline changes of accretion or erosion in the area.

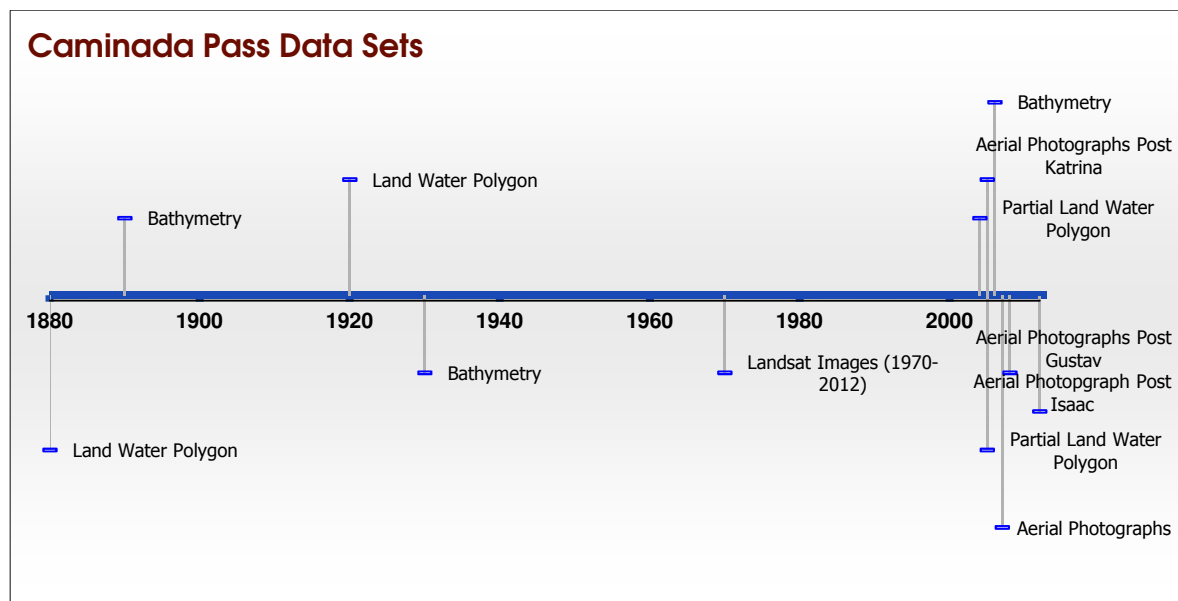


Figure 12: Timeline showing the temporal distribution of all of the datasets available for an analysis of Caminada Pass. Data that are available includes: bathymetry, Landsat images, land water polygons, and aerial photographs along with their corresponding dates.

Another goal is to evaluate the relative role of coastal processes such as RSL rise, hurricanes, longshore transport, and tidal deltas that have contributed to the evolution of the tidal inlet. The study illustrates general overall evolution and deterioration of the barrier islands, as well as short-term impacts due to storms.

### *Shoreline Analysis methods*

GIS revolutionized the process of shoreline mapping techniques and cartography (McBride et al, 1995). In order to gather an accurate analysis of shoreline change, charts, aerial photographs, and satellite imagery are collected and compared against one another to document shoreline evolution. Vector shoreline changes, derived from BICM volume 2: Shoreline Changes and Barrier Island Land Loss 1800's-2005 (Martinez et al., 2009), were used to determine the shoreline changes of coastal Louisiana overtime. With the use of the ArcGIS measuring tool from ArcGIS, the Caminada-Moreau headland and Grand Isle shoreline lengths and migration distances were determined for each timeframe.

### *Aerial photograph Analysis Methods*

Oblique Aerial photographs were obtained from BICM volume 1: Barrier Island Post-Storm Assessment (Westphal, 2009) for recent pre and post storm events. Aerial photographs are vital to this research, because they provide visual records of changes that occurred along the tidal inlet during pre and post storm occurrences. The photographs collected were taken from time periods 2005 (post Hurricane Katrina), 2007, 2008 (post Hurricane Gustav), and 2012 (post Hurricane Isaac). The photos from these storms were chosen to determine short-term influences of hurricane impacts to Caminada Pass. The photos from each of the time periods were then paired against one another to document local changes at Caminada Pass. The photos were mainly of Caminada Pass,

the western end of Grand Isle, the eastern end of Elmer's Island and the recurved spit protruding off Elmer's Island.

### *Bathymetry Methods and Analysis*

The bathymetric data used in this study was published by the Louisiana Comprehensive Monitoring Program (BICM) Volume 3: Bathymetry and Historical Seafloor Change 1869-2007 (Miner et al., 2009b). The data used from this report included historical data set from four time periods: 1890's, 1930's, 1980's, and 2006. The 2006 bathymetric surveys resulted in 4,762 line-km of bathymetric data taken from Sandy Point to Raccoon Island. More information on the data acquisition and data processing are available in Miner et al. (2009b). The 1980's surveys were constructed in digital form from single-beam hydrographic surveys conducted in 1986, 1988, and 1989. The 1930's surveys were conducted using soundings from hydrographic smooth sheets from the years 1933, 1934, 1935, and 1936 and used single-beam echo sounders. The 1880s surveys were constructed using soundings from hydrographic smooth sheets from the years 1878, 1883, 1886, 1889, 1891, and 1906 and were collected with lead lines and graduated rods (List et al., 1994). More information on the data acquisition for the 1980's, 1930's, and 1880s bathymetric surveys can be found in List et al. (1994).

Bathymetric values for each of the four time periods were used to construct digital, bathymetric grids. These grids were acquired from the USGS and were changed from 135 node spacing to 100m grid nodes to fit the 2006 bathymetric data, which was considered the best interval for the grid. These grids were used for seafloor elevation change (Miner et al., 2009a). Topographic survey sheets and satellite imagery were used and converted to XYZ points and assigned an elevation of 5m NAVD88 to take in account RSLR rates and erosion and accretion calculations. This process was used to take measurements in the intertidal zone and to prevent interpolation across islands during gridding (Miner et al., 2009a).

From the historical bathymetric datasets, cross sections across Caminada Pass were established at locations A, B, C, D, and E, as shown on figure 13. Transects were constructed using the line interpolation tool of ArcGIS and provide a means of examining the change in depth of the inlets at established locations through successive data sets. The data plots extracted from the cross sections were then entered into Excel to compare the growth of the inlet from the 1880s through 2006.

The averages were determined using the maximum depths and lengths of cross-sections A, B, C, and E. These averages were extracted from cross sections A, B, C, and E since they follow the same general trend, and cut across different areas of the tidal inlet. Inlet characteristics of cross section D were excluded because the cross section extends along the axis of the pass as opposed to across it.

### *Seafloor Change Analysis*

Seafloor change analysis was completed using ArcGIS by determining the differences between two bathymetric data sets. Miner et al., (2009a) did a similar seafloor analysis that determined the differences between two historical timeframes through *Surfer 8*, in which this method was based. The difference was taken between 1880s and 1930's, 1930's and 1980's, and 1980's and 2006. The results showed how much accretion and erosion has occurred during these time periods as indicated by positive (accretion) and negative (erosion) values determined by differencing bathymetric grids for select time periods. Vertical uncertainty for the historical bathymetric datasets was estimated to be a conservative  $\pm 0.5\text{m}$  (List et al. 1994). Uncertainty increases with the age of the bathymetric data set; therefore, the  $\pm 0.5\text{m}$  vertical uncertainty is used for all time periods (Miner et al., 2009).

### *Ebb tidal delta Volume Methods*

From the area change bathymetric maps, the ebb tidal deltas volume changes were calculated for each timeframe. The ranges include: 1880's to 1930's, 1930's to 1980's, 1980's to 2006, and for the total 1890's to 2006. The contouring tool was used in ArcGIS to determine the depth and length of the ebb tidal delta. The contours were set at +/- 1m of seafloor change for the 1890's-1930's, 1930's -1980's, and the 1890's-2006 map, but were set at +/-0.5 for the 1980-2006 map. The reason being the timeframe was a smaller interval than the other maps, and there was very little change that took place during this timeframe. The contours needed to get as close to the 0 contour as possible in order to get a proper area increase. The ArcGIS measuring tool was then used to calculate the area around each contoured that circled the ebb tidal delta sediment reservoir. The area was multiplied by the depth of each contour to determine the individual volume change. The volumes calculations were then added together to determine the total volume change for the ebb tidal delta from each time frame. A map of each of the bathymetric area changes for each timeframe is shown in figure 14. Other ebb tidal volume extraction studies were consulted (Walton and Adams, 1976; Hicks and Hume, 1997; Stauble, 1998;), but the method mentioned above was chosen, because it was the most logical one for this study due to the access to ArcGIS. Seafloor change maps were already conducted using ArcGIS, and the ebb tidal deltas were identifiable once the seafloor change maps were contoured.

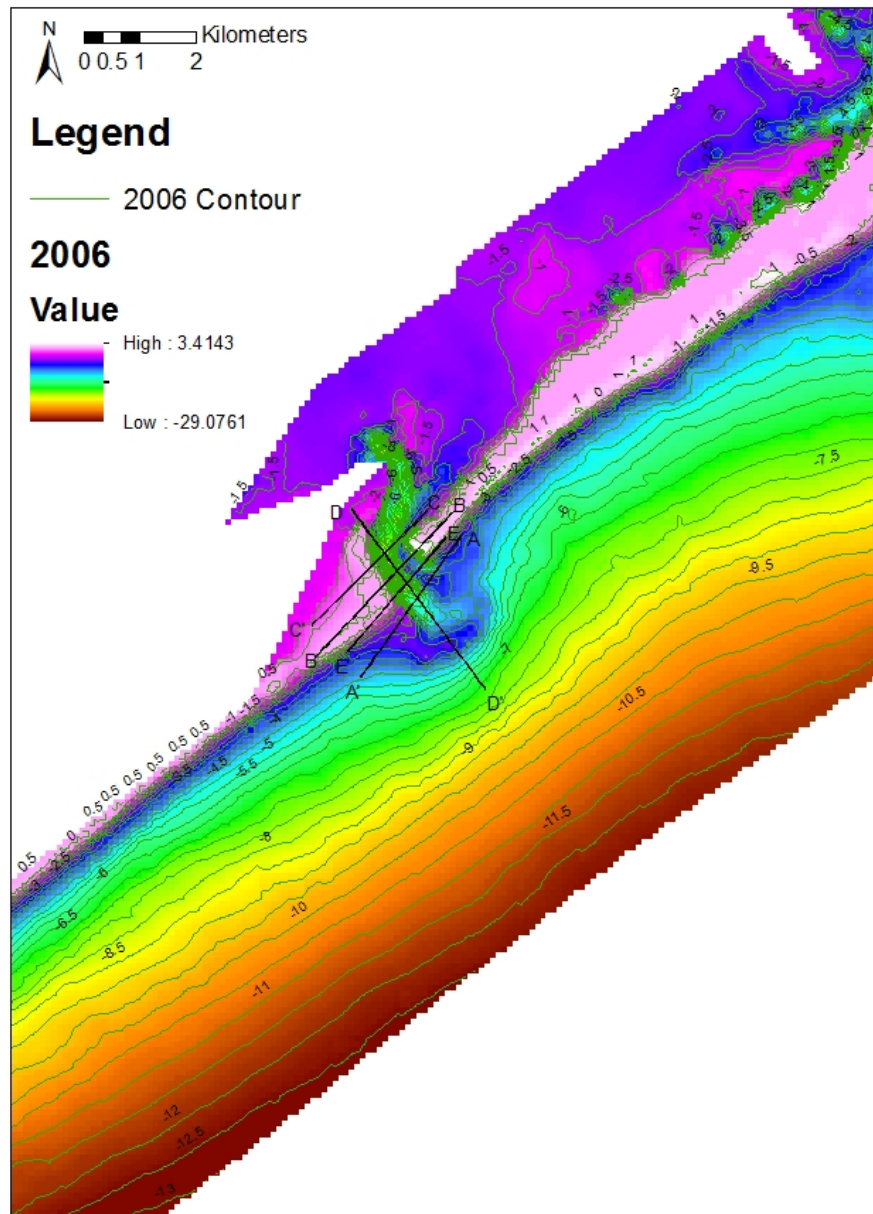


Figure 13: 2006 bathymetric map showing the placement of cross sections A, B, C, D, and E. These same cross sections were used for all historical time periods (BICM vol. 3). These grids were acquired from the USGS and were changed from 135 node spacing to 100m grid nodes to fit the 2006 bathymetric data, which was considered the best interval for the grid (Miner et al., 2009a).

### *Satellite Imagery*

Landsat Satellite Images (1-7) were used to document observable changes that occurred in Caminada Pass during 1972 to 2011. The Landsat satellite images used were taken from the USGS archives in Earth Explorer. The satellite images have a low resolution of 30m, but they are useful in observing changes and calculating changes within resolution of imagery of the adjacent island of Grand Isle and the Caminada Headland.

### *Grain Size Analysis Methods*

As part of the larger, more regional BICM effort to characterize the Louisiana coastal zone, sediment samples were systematically collected around Caminada Pass (Fig. 15). Samples were taken along a series of shore normal transects using hand scoops and ponar grab samplers (Kulp et al., 2011). Geographic coordinates were recorded at each sample location using a Differential Geographic Positioning (DGPS) (Kulp, et al., 2011). More information of the sediment sample analysis can be found in Kulp et al., (2011). All sediment samples around Caminada Pass were chosen to determine the sand/ silt analysis for each sample. The sand and silt content was determined by percentages and place in a ternary diagram based from the Shepard (1954) model for sand/ silt/ clay.



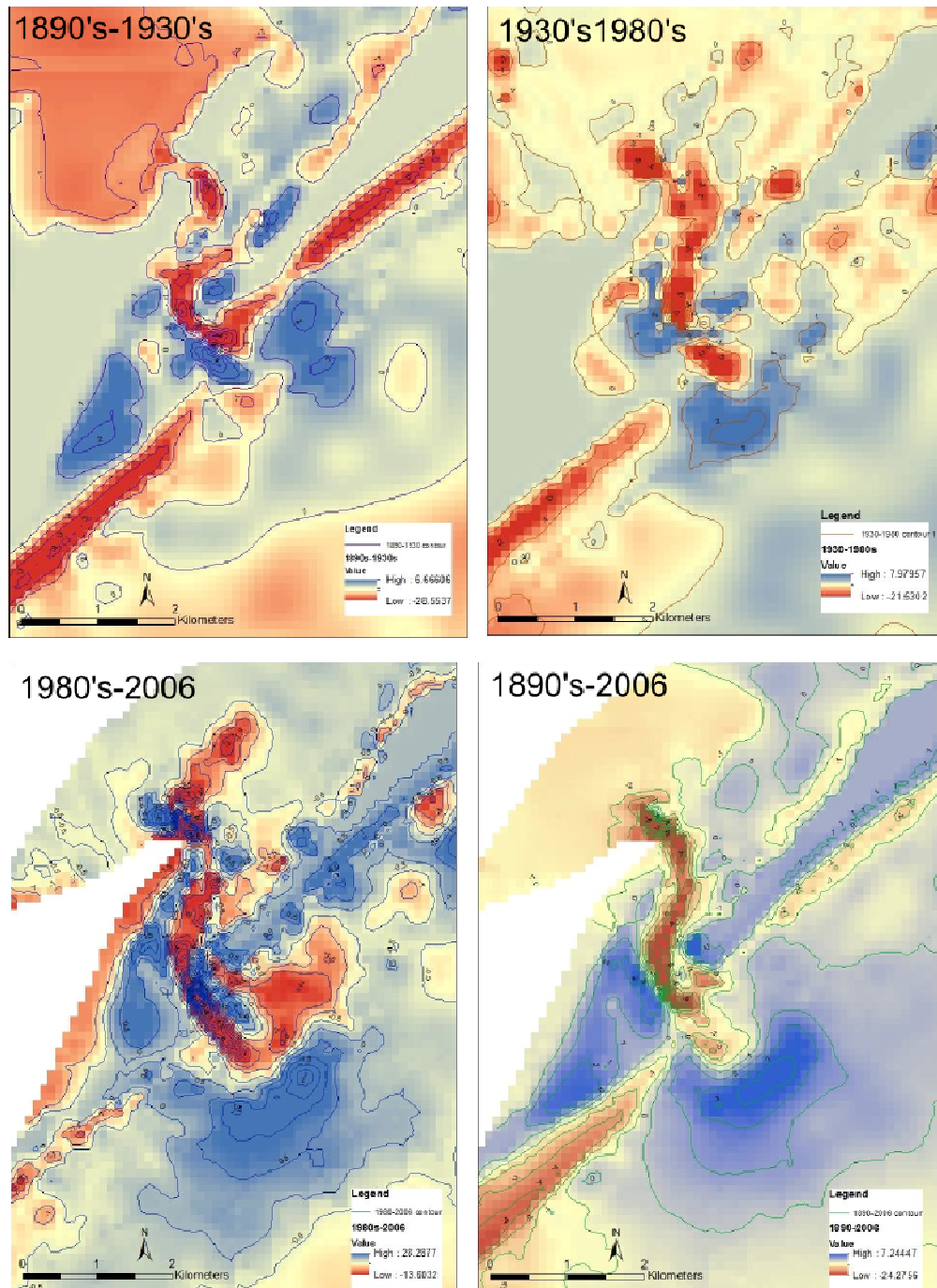


Figure 14: Maps displaying the ebb tidal delta volume changes for the 1890's-1930's, 1930's-1980's, 1980's-2006, and 1890's-2006. The blue represents the area of accretion, and the red represents areas of erosion for each timeframe. The volumes were determined by measuring area of each of the contours around the ebb tidal delta sediment reservoir (area in blue in front of the inlet channel) and then multiplying it by the depth of the contour (BICM vol.3). These grids were acquired from the USGS and were changed from 135 node spacing to 100m grid nodes to fit the 2006 bathymetric data, which was considered the best interval for the grid (Miner et al., 2009a).



Figure 15: Base map of the locations of the sediment samples collected around Caminada Pass. This map was created in ArcGIS using an ESRI satellite image of Caminada Pass and sediment samples locations that were compatible with the ArcGIS format from BICM volume 6. The date of the image is 2012.

## Results

### *Sediment Budget of Caminada Pass*

Studies have examined the coastal processes and shoreline evolution of the Caminada-Moreau Headland, and it has been found to have the highest erosion rates in the area (10 to 20 m/yr)(Morgan and Larimore, 1957; Penland and Boyd, 1982; Penland and Ramsey, 2003; Martinez et al., 2009), a result of limited sediment supply, high subsidence rates, and frequent occurrence of storms. Between 1880 and 2006, the Caminada-Moreau Headland and its shoreface to depths greater than 10m has lost  $1.05 \times 10^9 \text{ m}^3$  (Miner et al., 2009a). Based on sediment budget calculated by Harper (1977; Fig. 16) through a quantitative analysis of aerial photographs from 1952 and map overlays from 1972 and 1957, less than 5% of the volumetric loss of the Caminada-Moreau headland is redeposited back onto the Caminada-Moreau Headland. Moreover most of this redeposition is typically in the form of washover fans and within recurved spits and does not directly renourish the beaches and shoreface adjacent to areas of erosion. 41% of the sediment ( $2.3 \times 10^5 \text{ m}^3/\text{yr}$ ) eroded off the Caminada-Moreau Headland has been suggested to be captured along the western edge of the Barataria Pass Jetty; which means that the same amount ( $2.3 \times 10^5 \text{ m}^3/\text{yr}$ ) if not twice as much must pass through Caminada Pass and eventually making its way to Grand Isle and Barataria Pass due to longshore transport (Harper, 1977).

As seen in aerial photos and Landsat image, the Caminada Spit has been breached several times due to Hurricanes with the most substantial breaching taking place during Hurricane Flossy (1956) and Hurricane Betsy (1965) (Penland and Boyd, 1982) and more recently Hurricane Katrina (2005). The breaches in the Caminada Spit often close quickly due to abundant sediment eroding from the Caminada Moreau Headland to the west (Penland and Boyd, 1982).

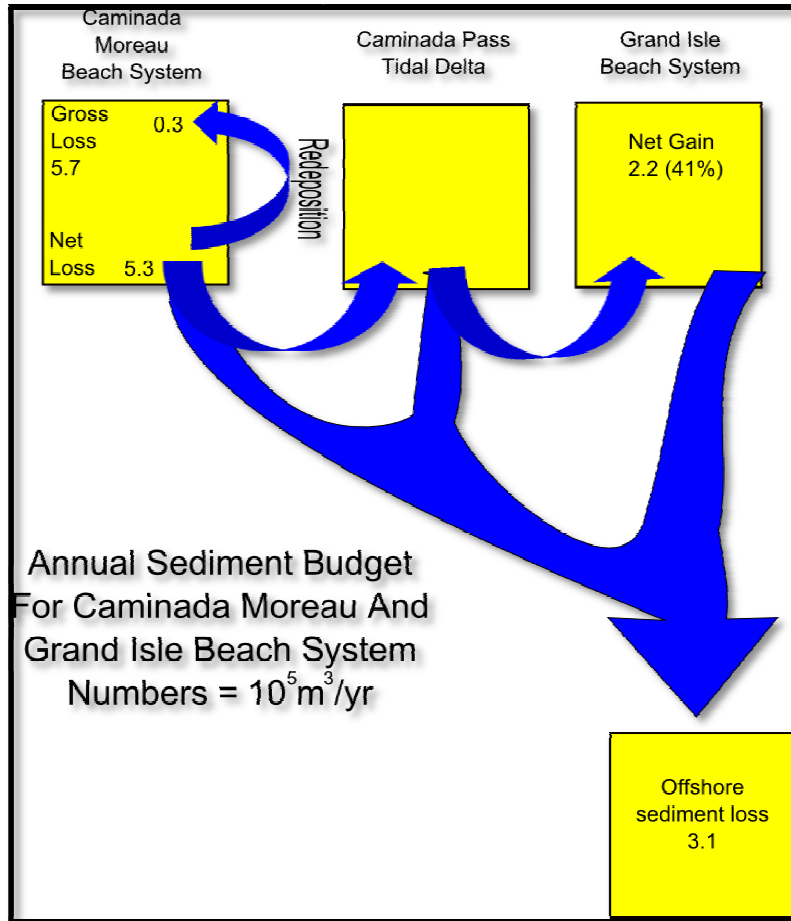


Figure 16: Conceptual model showing the sediment budget of the Caminada Moreau headland with an estimate of and much sediment is transported to the downdrift Grand Isle system into Caminada Pass (modified from Harper, 1977).

A rock jetty that is located on the eastern end of Caminada Pass (Fig. 17) was constructed in 1972 as a means to stabilize the eastern end of Grand Isle. In the time since its construction, the land area of Grand Isle increased from  $7.8\text{km}^2$  to  $8.8\text{km}^2$ , as a result of the jetty construction at Caminada and Barataria Pass, natural sediment bypassing which is defined as the transport of sediment from the updrift side of a tidal inlet to the downdrift side of a tidal inlet (FitzGerald, 1988), as well as beach nourishment programs.





Figure 17: 2007 oblique aerial photograph of the rock jetty that was placed at the western end of Grand Isle. The rock jetty was completed in 1972 to limit erosion of western Grand Isle. The jetty was extended seaward in 1987 (U.S. Army Corps of Engineers, 2012). The view for this image is to the northeast from southwest and is at an altitude of 61- 91m (Westphal and Penland, 2009). The photograph also shows southwest breaking waves and the Elmer's island inlet parallel beach can be seen in the background extending toward the bridge that connects the mainland to Grand Isle.

### *Tidal Prism and Cross Sectional Area*

Research conducted by FitzGerald et al. (2007) identified how an increase of wetland loss in Barataria Bay contributes to an increase of tidal prism and using Walton and Adams relationships (1976), the growth of ebb tidal deltas along the Barataria Bight. Acoustic Doppler Current Profiler (ADCP) surveys were conducted on Caminada Pass during peak ebb tides to illustrate the current discharge through the inlet and tidal prism (FitzGerald et al., 2007). The results (Fig. 18) of the research by FitzGerald et al. (2007) were compared to measurements from historical data from earlier time periods of Caminada Pass. The results show that the pass has quadrupled in cross

sectional area since the 1880s. Compared to the other inlets connecting Barataria Bay to the Gulf of Mexico, Caminada Pass underwent the least amount of enlargement during 1880-2006 (FitzGerald, 2007) (Table 1). The study also showed that the increase of tidal prism may diminish as the interior marsh area continues to be reduced due to tidal wave attenuation and frictional factors within Barataria Bay (FitzGerald et al., 2007; Howes, 2007). Howes (2009) calculated tidal prism to be  $5.79 \times 10^3 \text{ m}^3$  with a .407m tidal range at Caminada Pass, and proved through his tidal prism and inlet area study at Caminada Pass when compared to O'Brien/ Jarrett relationship are in close agreement.

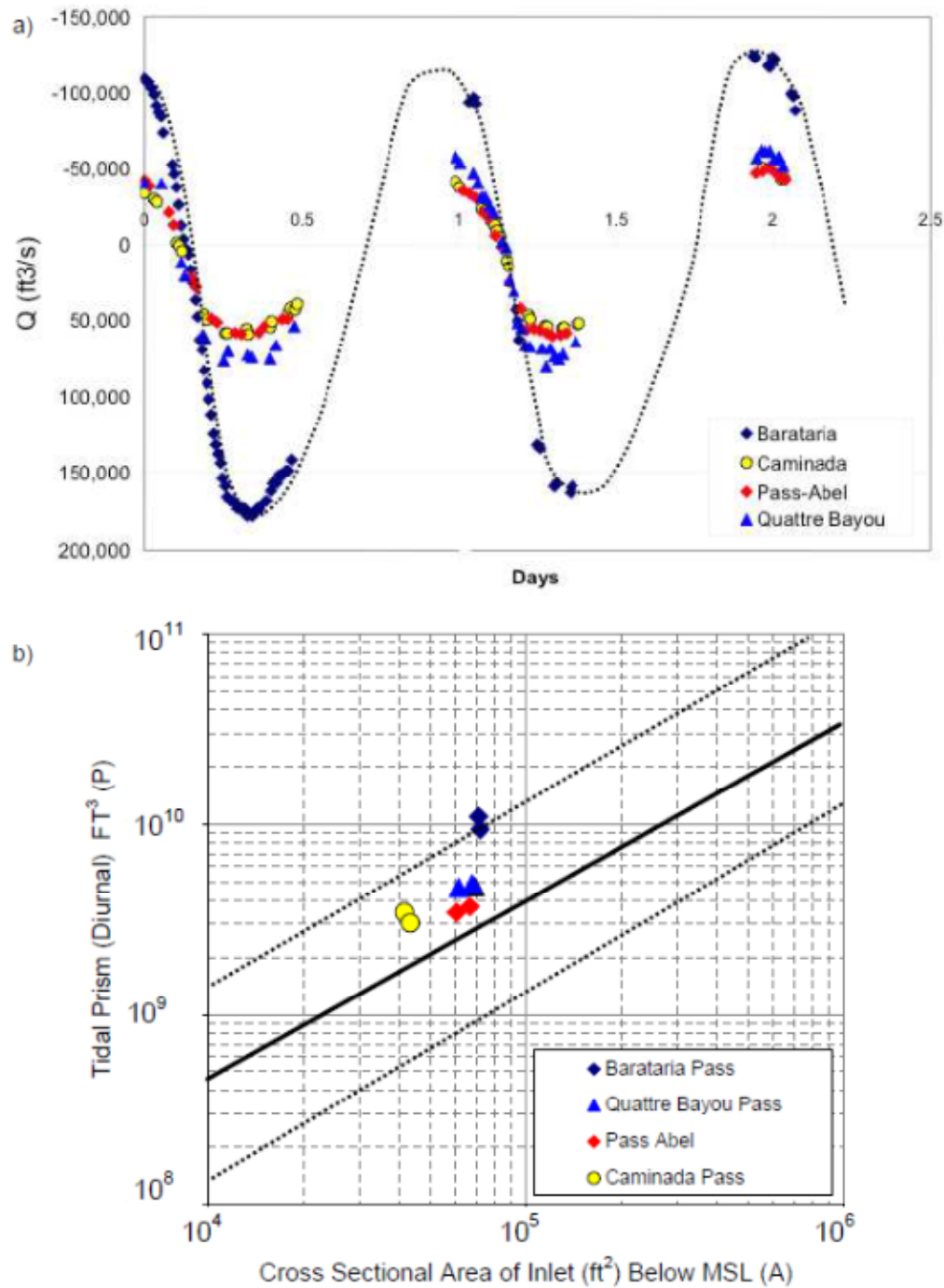


Figure 18: Figure A is a plot displaying discharge data collected for the Barataria Bay tidal inlets, and serves as a basis for determining tidal prism for two ebb tidal cycles taken during the day during the summer of 2006 for each of the Barataria Bay tidal inlets. When the discharge data is then plotted against the cross sectional area for each of the inlets (FitzGerald et al., 2007), a comparison can be made to the Jarrett (1976) curve, which describes a linear relationship between cross sectional area and tidal prism unjettied inlets (heavy black line). Figure is from (FitzGerald et al., 2007).

Total Cross Sectional Area (m <sup>2</sup> )					
Year	Abel	Barataria	Caminada	Quatre Bayou	Total X-sect area
1880	0	3996	809	133	4938
1930	395	7079	1353	2590	11417
1980	4193	8712	1532	3777	18214
2006	6669	7541	3372	6726	24308

Table 1: Table displaying the cross sectional area of each of the Barataria Inlets during the time periods 1880-2006 (FitzGerald et al., 2007).

### *Aerial Photography*

The following sections are a collection of aerial photos of Caminada Pass and the adjacent islands of Grand Isle and Elmer's Island. They document the short-term impacts of the recent hurricanes that have impacted this area. These storms include: Hurricanes Katrina and Rita (2005), Hurricane Gustav (2008), and Hurricane Isaac (2012). These photos are compared to the year 2007, when no storms occurred, to observe the before and after views and the recovery rates of the islands.

### *Geomorphic Description of Aerial photographs, 2005 Post Katrina and Rita*

#### *Image 467*

This image (Fig. 19) is a view to the north showing Caminada Pass and the western of Grand Isle, which is displayed by a yellow arrow in the figure. The discontinuous inlet-parallel beach that is formed from the recurved spit off Elmer's Island can be seen in the photo. The Cheniere Caminada is also discontinuous in the northwest side of the photo. The beach on Grand Isle is visible in the photo directly adjacent to the jetty. The beach on Grand Isle is nearly absent, and



subaerial sand is absent between the mainland of Grand Isle and the rock jetty. It extends outward from the west end and thins along the island toward the east.

*Image 468*

This is an image (Fig. 19) of Elmer's from the direction of east to west and is indicated by the orange arrow in the figure. The island appears to be discontinuous and is almost entirely subaqueous as pointed out by the green arrow. Little vegetation is visible along Caminada Pass. More vegetation is present toward the bayside farther west in the photo along Elmer's island. The island is nearly breached, and there is a narrow area of subaerial sand that connects the vegetated side with a beach to the non-vegetated side with a smaller beach. Toward the back of Caminada Pass to the north, the sandy beach thins significantly.

*Image 469*

Image 469 (Fig. 19) provides a better view of the breach that developed during Hurricanes Katrina and Rita. The narrow area of land connecting the east and west side of Elmer's island is a vegetated area extending into the backbarrier. Along the gulf side, the beach is absent and instead, there exists a series of small sandbars. The beach on the western side of Elmer's island is a mixture of sand and vegetation. The sand had been transported into the vegetation and the remainder of the beach is absent.

*Image 470*

Image 470 (Fig. 19) displays Caminada Pass in the direction from Elmer's Island toward the northeast. This image shows the inlet-parallel beach off Elmer's Island extending toward the terminal end of Caminada Pass. The beach appears to be subaqueous on the gulfside of Elmer's Island. The mixture of vegetation and sand is thick on the gulfside of Elmer's Island and thins out as it enters toward the back end of Caminada Pass. Toward the terminal end of the inlet-parallel

beach, a thick area of sand is apparent and is in the form of a drumstick shape as displayed by the purple arrow in the figure.

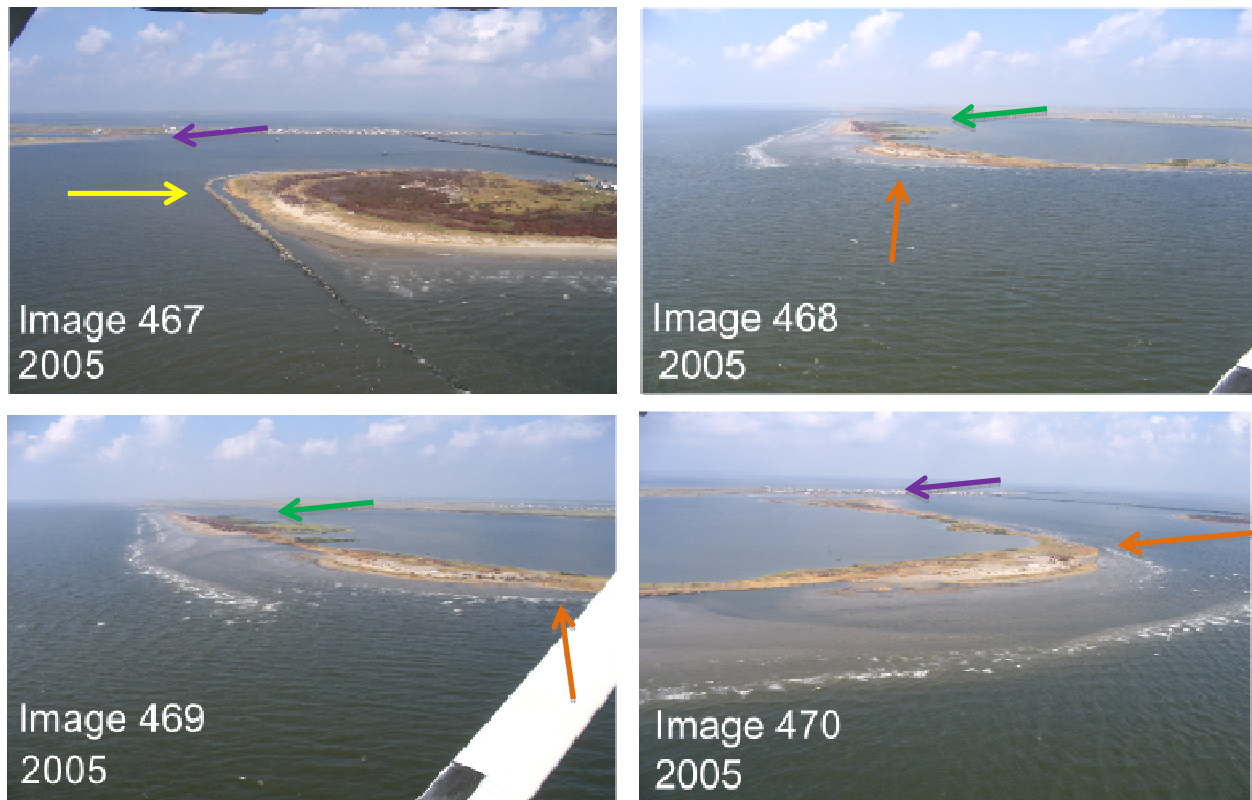


Figure 19: Aerial Images 467, 468, 469, and 470 were taken post Hurricanes Katrina and Rita in 2005. The images display the damages of Grand Isle and Elmer's Island due to these hurricanes. Some of the beach sediment is subaqueous on the gulfside of the pass on both islands, and Elmer's island has been breached, which is represented by the green arrow. The orange arrows represent the eastern end of Elmer's Island. The yellow arrow represents the western end of Grand Isle and the purple arrow represents the terminal end of the Elmer's Island spit.

### *Geomorphic Description of Aerial Photographs, 2007*

#### *Image 1915*

Image 1915 (Fig. 20) displays the tip of the western end of Grand Isle as displayed by the yellow arrow in the figure. The direction of this photo is from the southwest to the northeast. The sand from the beach is thickest around the western most point on the gulf side and thins out as the

beach extends east. The waves refract from the southeast toward the northwest, and break along the western point and rock jetty. The sand from the beach is the most narrow and almost non-existent between the east end of the rock jetty. It extends outward from the west end and thins along the island toward the east. The inlet-parallel beach can be seen in the background extending toward the Grand Isle Bridge. The purple arrow indicates the terminal end of the inlet parallel beach.

*Image 1902*

This image (Fig. 20) is of Elmer's Island from the direction east to west as displayed by the orange arrow in the figure. Wet and dry sand appears to be on the gulf side beach with a shallow pool of water in the middle, and vegetation is observed on the bayside. The beach is thickest at the edge of the pass in the pivot point, and thins out as the inlet-parallel beach extends into the pass toward the north. Vegetation is present on the bay side and is thickest along the open side away from the pass, and thins toward the north. Fragmentation is also present along the gulfside of Elmer's island and is displayed by the green arrow.

*Image 1899*

This image (Fig. 20) is similar to 1898, but displays the area more to the east, but there is a better view of the hummocky curvature, which is displayed by the red arrow, along the inlet-parallel beach off Elmer's Island. The inlet parallel beach's terminal end is displayed by the purple arrow. More detail of this feature is described below.

*Image 1898*

Image 1898 (Fig. 20) is of Elmer's Island directly looking at the pivot point when the inlet parallel beach extends into Caminada Pass toward the north. There appears to be dry and wet sand on the beach on the gulf side, and vegetation on the bay side. The inlet-parallel beach has a

hummocky curvature as displayed by the red arrow as it enters into the pass. It curves and thins out toward the east with it terminates at the location displayed by the purple arrow. No vegetation is observed on the end of the inlet-parallel beach, but the vegetated overwash behind the inlet-parallel beach is thickest inside the curves.



Figure 20: Aerial Images 1915, 1902, 1899, and 1898 were taken during 2007. The images Grand Isle and Elmer's Island, and provides a good example of what the islands look like when they are not impacted by hurricanes. The beaches are thicker a vegetated overwash is observed on the gulfside of the islands. The orange arrows represent the eastern end of Elmer's Island. The yellow arrow represents the western end of Grand Isle and the purple arrow represents the terminal end of the Elmer's Island spit. The red arrow displays the hummocky curvature of the inlet parallel beach.

## *Geomorphic Description of Aerial Photographs, 2008 Post Hurricane Gustav*

### *Image 425*

Image 425 (Fig. 21) shows the western tip of Grand Isle, which is displayed by the yellow arrow, post Hurricane Gustav from south toward north. The rock jetty is the focal point of this photo as well as the vegetation on Grand Isle. The beach is almost entirely absent, but the vegetation in the interior is thick. Subaerial sand is also absent between the mainland and the rock jetty. Subaqueous sand is visible where the beach used to be.

### *Image 428*

This image (Fig. 21) displays Caminada Pass in the direction from south to north and is west of image 425. The image shows the southern tip of the western end of Grand Isle and Cheniere Caminada. The inlet-parallel beach of sand off of Elmer's island is seen on the left side of the photograph and is indicated by the purple arrow. The inlet-parallel beach is discontinuous and thins out as it moves eastward. The Cheniere Caminada is also discontinuous and flooded.

### *Image 440*

This image (Fig. 21) is of Elmer's Island from the viewpoint southeast toward the northwest. It displays the eastern end of Elmer's island, which is distinguished by the orange arrow, as it extends into Caminada Pass along the pivot point. The beach is absent, but subaqueous sand is visible where the beach was once visible. The vegetation is still present, but some of the vegetation is brown. The island has been breached as the parallel inlet beach entered the pass. The breach is indicated by the blue arrow.

### *Image 438*

This image (Fig. 21) of Elmer's Island is taken from the viewpoint of southwest toward the northeast. The image displays the Elmer's island inlet-parallel beach extending toward the back side of the inlet. This is a continuation of image 440, and shows more of the spit than the previous photo. Sand is absent in the photo with the exception of a small area in the northeast corner. There is visible vegetation that extends into Caminada Bay above an overwash fan. The island is breached in the bottom right corner. The waves are entering into the pass from southeast to northwest.

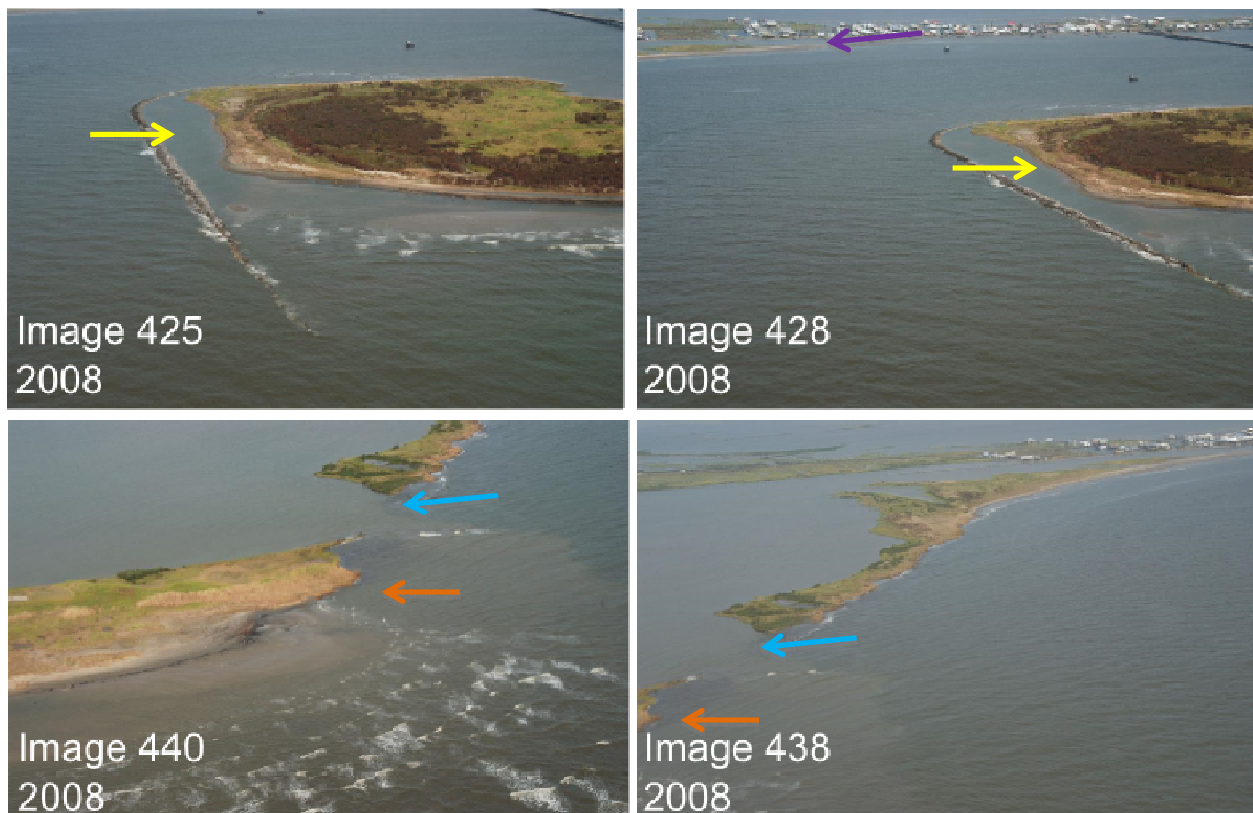


Figure 21: Aerial Images 425, 428, 440, and 438 were taken post Gustav in 2008. The images display the damages of Grand Isle and Elmer's Island due to this hurricane. The beaches are absent on both islands and Elmer's island has been breached along on the inlet-parallel beach extending into Caminada Pass. The breach is indicated by the blue arrow. The orange arrows represent the eastern end of Elmer's Island. The yellow arrow represents the western end of Grand Isle and the purple arrow represents the terminal end of the Elmer's Island spit.

### *Geomorphic Description of Aerial Photographs, 2012 Post Hurricane Isaac*

*Image 3451*

The focal point of this image (Fig. 22) is the western end of Grand Isle, the eastern end of Caminada Pass, Cheniere Caminada, and Caminada Bay. The viewpoint is toward the north, and Grand Isle is indicated by the yellow arrow. The terminal end of the inlet parallel beach has prograded to the Grand Isle Bridge where it terminates, which is indicated by the purple arrow. The Grand Isle beach is absent except along the rock jetty where the beach is intact but discontinuous. The waves on the Caminada pass side of the Grand Isle appear to be coming in from a northerly direction toward the southeast. The interior is still filled with vegetation. *Image 3650*

This image (Fig. 22) provides an east to west view of the gulf side of Elmer's Island. The beach on the gulf side of Elmer's Island is narrow, almost absent, and discontinuous with two major breaches that are indicated by the green arrow. Pools of water separate some the beach on Elmer's island from the vegetation. Vegetation is located on the bay end of Elmer's island in an overwash fashion. In the image, the waves are hitting the beach along widest and most concentrated areas in a northeasterly direction. As the waves enter into the pass, it hits the sand inlet-parallel beach at a northwesterly direction.

*Image 3728*

This is an image (Fig. 22) of the inlet parallel beach on the eastern end of Elmer's Island. The viewpoint of this photo is from the south looking toward the north. The inlet parallel beach takes has a hummocky curvature, which is indicated by the red arrow, as it moves toward the northern end of the pass. Sand fills up the pass side of the inlet parallel beach with vegetation on the bay side. Sand bars are also visible on the pass side of the island. The vegetation terminates as you move to the north where the inlet parallel beach is breached, which is indicated by the blue arrow, but is visible again at the northern edge of the breach. The inlet parallel beach is more vegetated on the northern side of the breach. The inlet parallel beach changes directions toward the east and extends out of the frame.



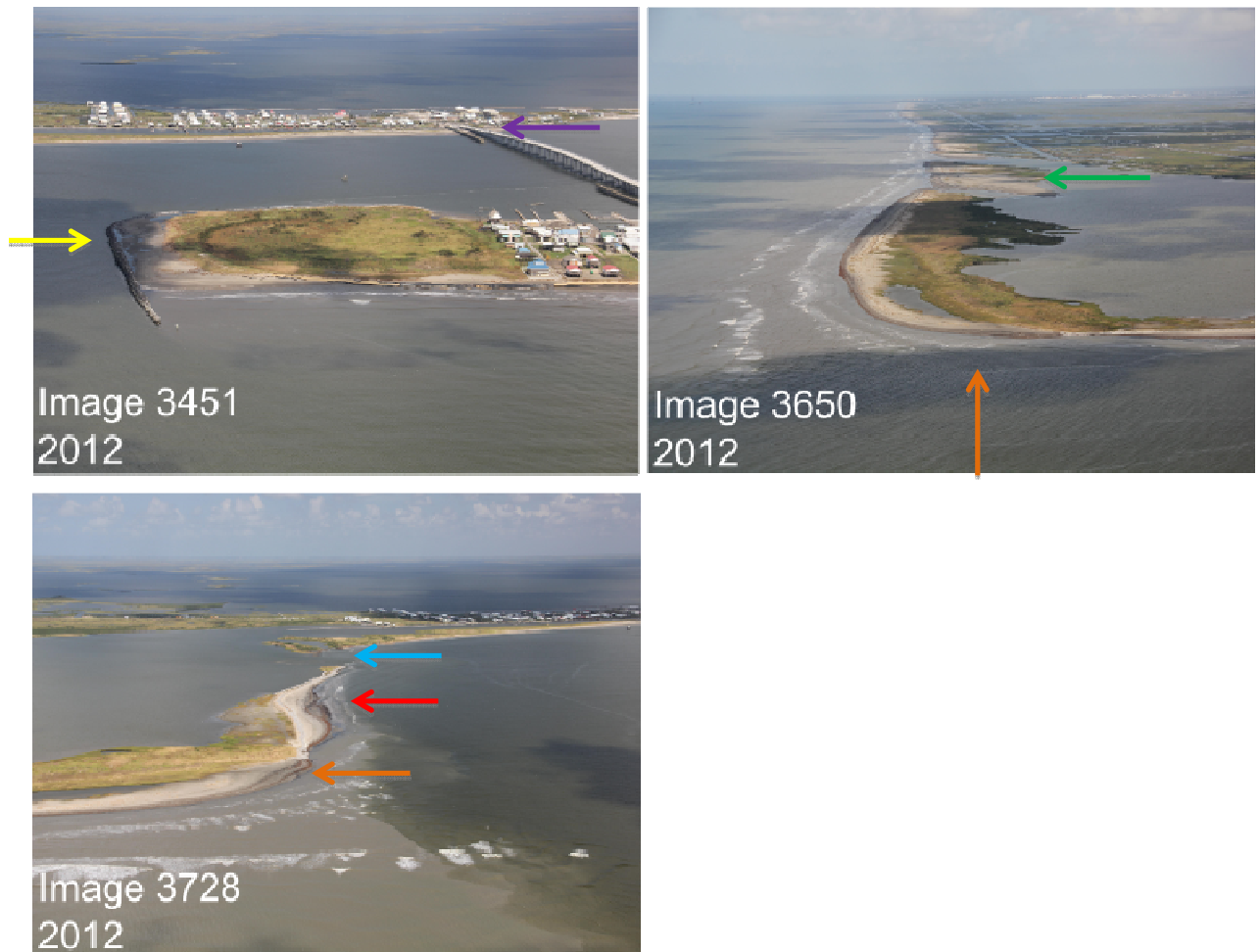


Figure 22: Oblique aerial Images 3451, 3650, and 3728 were taken post Isaac in 2012. The images show the modification of Grand Isle and Elmer's Island due to Hurricane Isaac. The beaches on both islands are nearly absent and the inlet-parallel beach of Elmer's island has been breached which is indicated by the blue arrow. The darker areas in the water are cloud coverage. . The orange arrows represent the eastern end of Elmer's Island. The yellow arrow represents the western end of Grand Isle and the purple arrow represents the terminal end of the Elmer's Island spit. The green arrow represents the discontinuous nature of Elmer's island along the gulfside. The red arrow displays the hummocky curvature of the inlet parallel beach.

### *Summary of Oblique Aerial Imagery*

These oblique aerial images have been used to compliment the other datasets of this research by providing clear and close up pictures of some of the modifications that have occurred to Caminada Pass in recent history. The photographs provide a good example in how resilient the



adjacent islands of Caminada Pass can be despite the constant threat of storms, since the beaches are built up again within a couple of years

Major observations include: growth of the inlet-parallel beach off Elmer's island and its response to storm impacts; buildup and growth of the beaches on Grand Isle and Elmer's island post storms, and how quickly the beach can be diminished after one hurricane; and vegetation plays a vital role in stabilizing the islands during and after storms since it is still visible after a storm has passed through.

### *Profile Results*

There were five profiles constructed across Caminada Pass in order to assess the bathymetry and bathymetric change of the inlet through time Transects A, B, C, and E extend across Caminada pass connecting Grand Isle to Elmer's Island, and D extends through the pass connecting the backbarrier to the gulfside. The same cross section lines were used for all of the time periods giving varying results. Figure 23 displays a map of the locations of the cross section across all time periods.

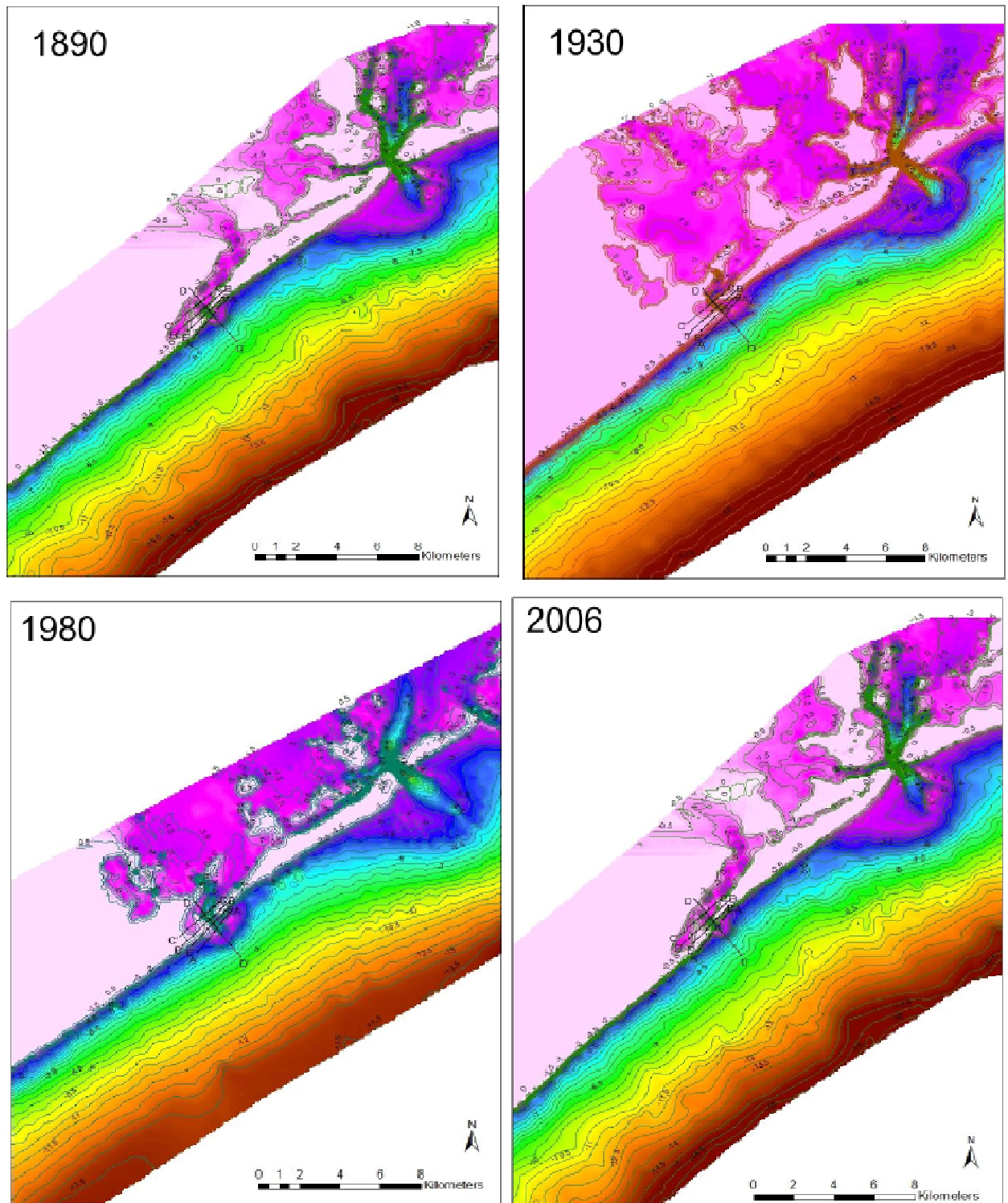


Figure 23: Bathymetric base maps showing the distribution and trends of cross sections. These profiles were used to quantify inlet area changes for each of the time periods (1890, 1930, 1980, 2006) and provide an opportunity to document inlet throat and flanking channel morphology (BICM vol. 3).

### *Cross Sectional Profile A-A'*

Profile A-A' (Fig. 24) trends toward the northeast for 3.5km along the gulf side of the pass. As in the case for all of the profiles the locations and trends of profiles remained the same for each of the time periods regardless of the creation or disappearance of subaqueous and subaerial features.

The 1880s cross section of the tidal inlet channel has a maximum depth of -3.5m relative to mean sea level (MSL) and is 300m wide. The 1930's cross section has a maximum depth -2.2m relative to MSL and is 400m wide. The 1980's area plot indicates cross section enlargement due to the tidal inlet channel widening and deepening with dimensions of a maximum depth -4.8m relative to MSL and is 550m wide. The 2006 plot provides a glimpse of the inlet during its largest size with a maximum depth of -5.9m relative to MSL and is 600m wide.

### *Cross Sectional Profile B-B'*

Profile B-B' (Fig. 24) is a northeast, 3km long trend that goes through the center of the tidal inlet channel. There are two cross sections going through the tidal inlet channel ensure correct measurements will be taken for all time periods since there is lateral movement of the pass. The second cross section will be seen in Cross Sectional Profile E-E'.

The 1890's cross section of the tidal inlet channel has a maximum depth of -3m relative to MSL and is 500m wide. The 1930's cross section has a maximum depth of -4.5m relative to MSL and is 400m wide. The 1980's cross section has a maximum depth of -5.6m relative to MSL and is 550m wide. The 2006 cross section has a maximum depth of -10m below sea level, and is 700m wide.

### *Cross Sectional Profile C-C'*

Profile C-C' (Fig. 24) is a northeast, 3km long trend that goes along the bayside of the pass. The 1890's cross section of the tidal inlet channel has a maximum depth of -3m relative to MSL and is 300m wide. The 1930's cross section has a maximum depth of -5.1m relative to MSL and is 500m wide. The 1980's cross section has a maximum depth of -5.1m relative to MSL and is 700m wide. The 2006 cross section has a maximum depth of 7.1m relative to mean seal level and is 800m wide. The reasoning for this distance across in the 1980 and 2006 plots, as opposed to the 1890 and 1930 plots, is due to the lateral movement of the inlet toward the west and the western end points are below MSL instead of land in the backbarrier of Elmer's Island.

#### *Cross Sectional Profile D-D'*

Profile D-D' (Fig. 24) is a northeast, 4km long trend that extends through the inlet channel. This cross section is different from the other cross sections because it connects the bayside to the gulfside through the inlet throat. The 1890's plot of bathymetry shows a gradually decreasing depth from sea level to approximately -8m deep. From left to right, the trend decreases until it reaches -2m at 2000m when there is a sudden increase to -1.1m at 3000m. The depth decreases again to -3.2m. There is one last peak at 2200m, where it tapers off to -7.8m at 3800m.

The 1930's plot extends 3800m from sea level to -7.5m in depth. The cross section has a steeper decrease from start to finish with a major peak to a greater depth in between. The peaks and troughs on the plot are smaller than the 1980's plot. The plot has key troughs at -4.1m in depth at 900m, -5.1m in depth at 1500m. The key peaks occur at -3m in depth at 1100m and -1m in depth at 1700m. The cross section then tapers off decreasing to -7.5m in depth.

The 1980's plot extends from above sea level to the 3800m. The cross begins with a steep decrease in depth reaching -6m at 1200m followed by a steep increase to -3m at 1500m. It decreases slightly again to -3.5m, and then it gradually increases to its highest peak at -2m at 3000m where it tapers off to -7.1m at 3800m.

The 2006 cross section also has a steep decrease in depth at 300m where it reaches a depth of -7.1m at 900m. It gradually increases to -3.5m at 1550m. It falls again to -6m at 800m. It gradually increases to its highest peak at -2.2m at 3000m before it tapers off to -6.9m at 3800m.

#### *Cross Sectional Profile E-E'*

Profile E-E' (Fig. 24) is a northeast, 2.8km long trend that extends through the center of the tidal inlet channel. This cross section covers some of the measurements a little more accurately (more specifically the 1890's cross section) that was not seen as well in B-B'.

The 1880s cross section has a maximum depth -4.1m relative to MSL and is 300m wide. The 1930's cross section has a maximum depth of -4m relative to MSL and is 400m wide. This graph is better seen in B-B' because it better accounts for its lateral movement from 1880s to 1930's. The 1980's cross section has a maximum depth of -4.8m relative to MSL and is 600m wide. The 2006 cross section has a maximum depth of -8.5m relative to MSL and is 600m wide.

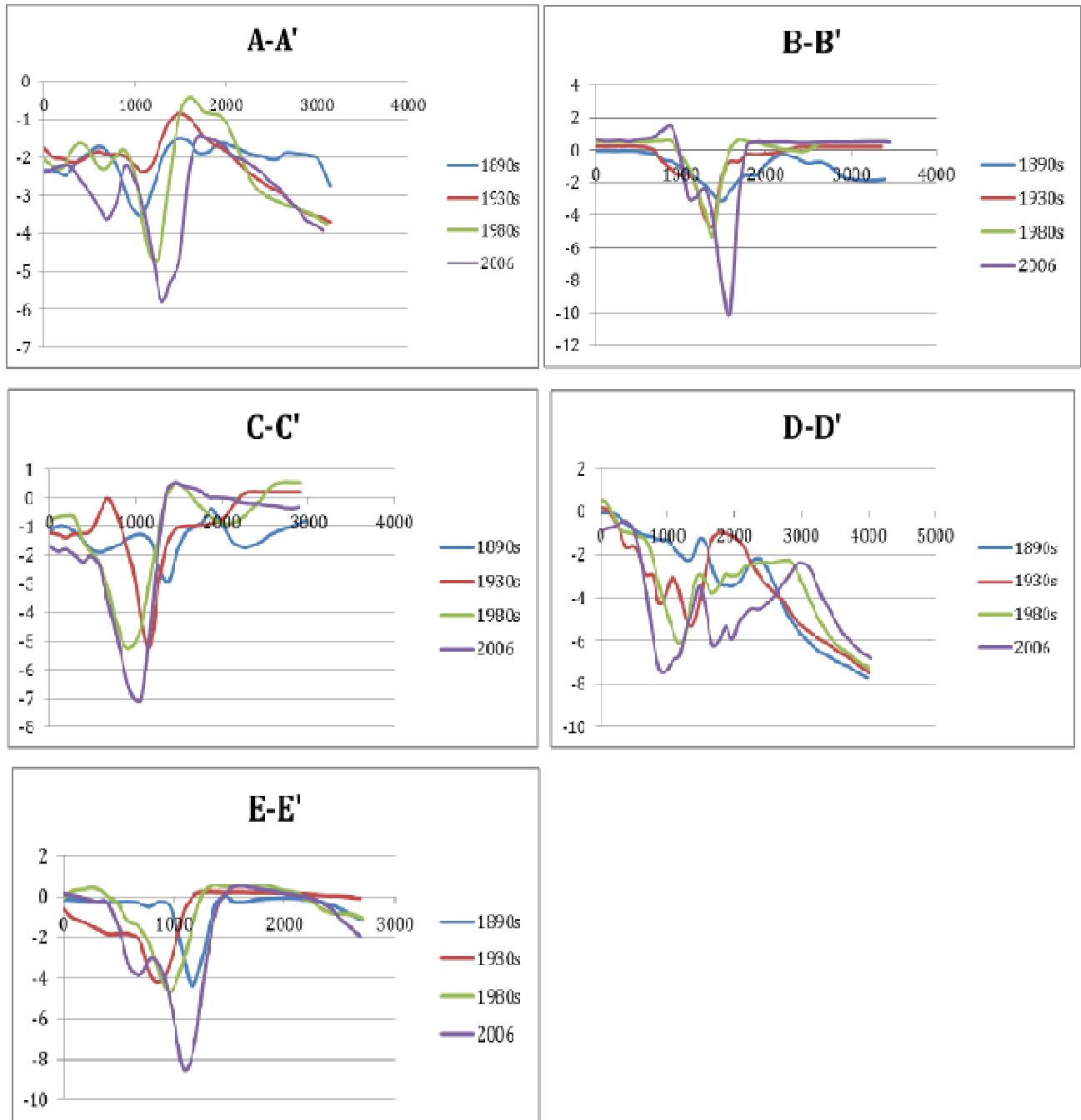


Figure 24: Bathymetric profile plots for A-A', B-B', C-C', D-D', and E-E' during the time periods: 1890's, 1930's, 1980's, and 2006. Caminada Pass has shown an overall widening and deepening through time based on these plots. The inlet has also undergone lateral movement to the west between 1890 and 1930. Cross sections B-B' and E-E' proves this movement because the 1930's cross section is better observed in B-B' and the 1890's cross section is seen clearer in E-E'.

### *Summary of Profile Results*

The cross sections from the 1890's show a small tidal inlet with an average depth of -3.4m relative to MSL along the length of the thalweg below sea- level and average width of 350m across the inlet. The inlet increased in depth by 0.6m and increased in length by 75m from the 1880's. The average depth, from the 1930's cross sections, was -4.0m relative to MSL, and the average width across the inlet was 425m. The inlet increased in depth by 0.6m and but increased in length by 75m from the 1880's. The average depth, from the 1980's, was -5.1m relative to MSL and the average width across the inlet was 600m. According to these averages, there was an increase of 1.1m depth and 175m in width from the 1930's to the 1980's. The average depth, from the 2006 bathymetry was -7.9m relative to MSL and the average width across the inlet was 675.2, or a net increase of 2.8m depth and of 75.2m increase in width.

### *Cross-section Comparisons*

The cross-sectional area was computed for each timeframe by multiplying the average width by the average depth from each cross-section, and then the results were compared to the cross-sectional area that was computed by FitzGerald et al. (2007) and FitzGerald et al (2004). The comparisons are listed in Table 2. Overall, the cross-sectional area derived from the profiles was much larger than the cross-sectional area from FitzGerald et al., 2007. The larger cross-sectional area from the profile results is probable since there were cross-sections that extended through the backbarrier and ebb tidal delta for each time frame. For the 1890's results, the cross-sectional area from the profiles was  $381\text{m}^2$  larger than Fitzgerald et al., (2007). For the 1930's results, the cross-sectional area from the profiles was  $325\text{m}^2$  larger than Fitzgerald et al., (2007). For the 1980's results, the cross-sectional area was  $1513\text{m}^2$  larger than Fitzgerald et al., (2007). For the 2006 results, the cross-sectional area was  $1960.6\text{m}^2$  larger than Fitzgerald et al., (2007).

### Caminada Pass Cross-sectional Area (m<sup>2</sup>)

Year	Profile Cross-sectional Area	FitzGerald et al., 2007 Cross-Sectional Area
1880	1190	809
1930	1678	1353
1980	3045	1532
2006	5332.6	3372

Table 2: Table comparing the cross-sectional area from the profile results and the cross-sectional areas derived from FitzGerald, et al. (2007). Overall, the profile cross-sectional areas were larger than the FitzGerald et al., (2007) cross-sectional area.

### *Sediment Samples results*

The following is a list of all of the sediment samples in and around Caminada Pass. The locations for each of the sediment samples are shown in figure 25. The sediment samples used were SUE\_139, SUE\_138, SUE\_137, SUE\_136, SUE\_135, SUE\_132, DIC\_244, DIC\_245, DIC\_246, DIC\_86, DIC\_87, and DIC\_88. The mean sand and silt percentages of the samples are provided in Table 3. The samples found on and around the beach are written italics. The samples were shown to contain sand ranging between 85 and 100% with relatively much less silt (0-15%). The samples that are found in the channel and tidal deltas are written in bold. A ternary diagram (Fig. 26), based on Shepard's diagram (1954), illustrates the variability of sand and silt content within the samples. All of the samples were located closest to the sand apex of 100% sand, with some of the samples plotting in the silty sand division. An even more detailed breakdown of the sediment samples is provided in Table 4. This table divides the sand content into very coarse, coarse, medium, fine, and very fine, and breaks the silt category into very coarse, coarse, medium fine, and very fine.



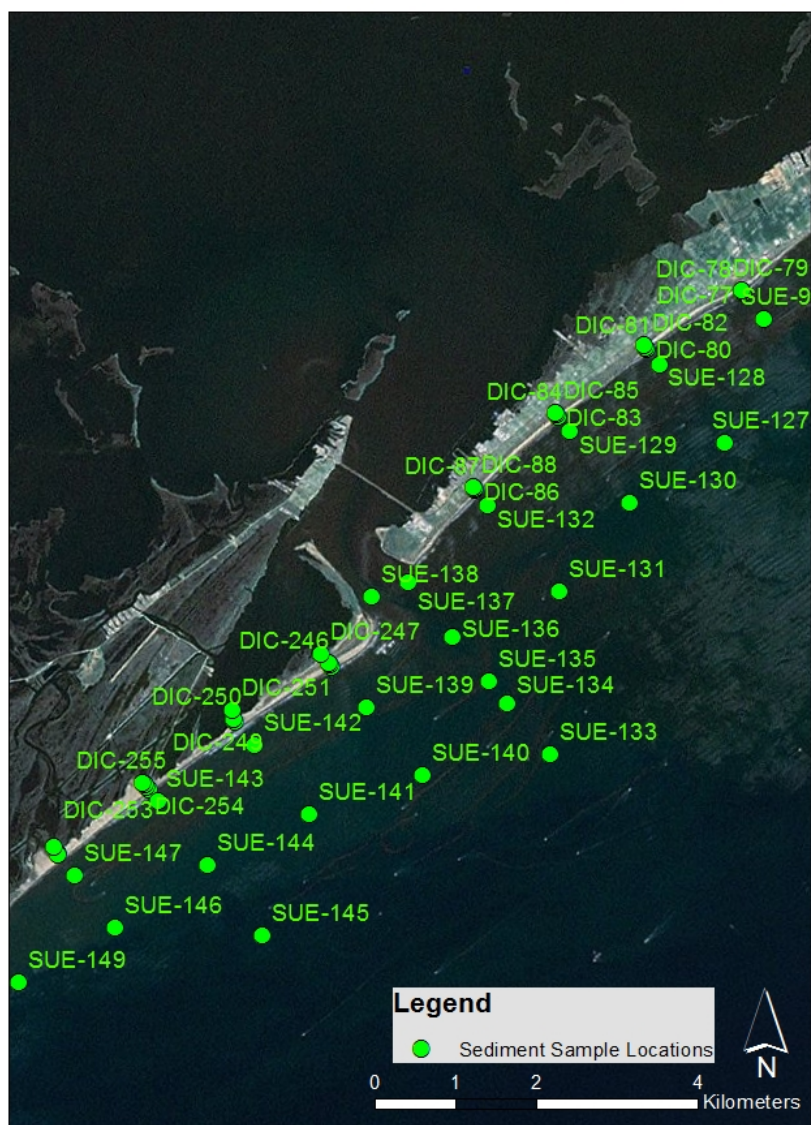


Figure 25: Base map of the locations of the sediment samples collected around Caminada Pass. This map was created in ArcGIS using an ESRI satellite image of Caminada Pass and sediment samples locations that were compatible with the ArcGIS format from BICM volume 6. The date of the map is 2012. Majority of the sediment samples are found along the beaches of Grand Isle and Elmer's island. Sediment samples are also located in the ebb tidal delta and one sample is located directly in the inlet throat.

Sediment Samples	Mean Sand (%)	Mean Silt (%)
SUE_139	89	11
SUE_138	95.9	4.1
SUE_137	84.9	15.1
SUE_136	95.4	4.6
SUE_135	87.8	12.2
SUE_132	90	10
DIC_244	98.7	1.3
DIC_245	100	0
DIC_246	100	0
DIC_86	99.1	0.9
DIC_87	100	0
DIC_88	100	0

Table 3: Table displaying the mean sand and silt percentages of all of the sediment used in this research. The yellow coded samples are samples found in the tidal delta and the channel and the purple coded samples are found on and around the barrier islands. Each of the samples contained a majority of sand.

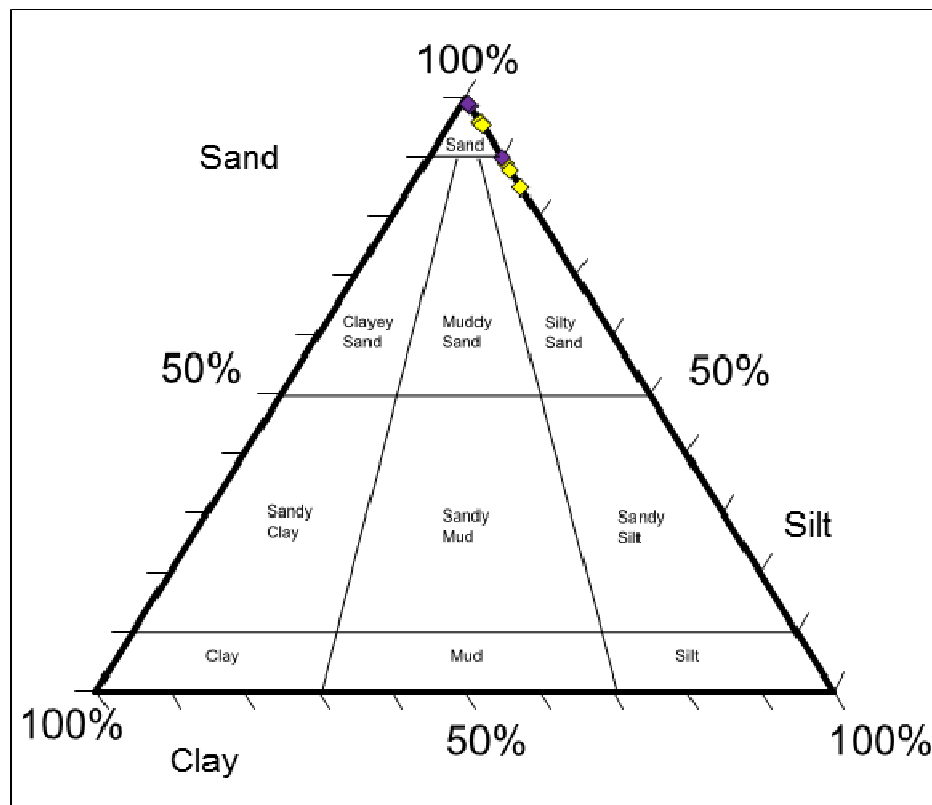


Figure 26: Ternary Diagram (based on Shepard, 1954) displaying the distribution of the sediment samples around Caminada Pass. Most of the samples are located in the sand category with a few located in the silty sand category.

Sediment Samples	Very Coarse Sand (%)	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Very Fine Sand (%)	
SUE_139	0	0	2.8	61.3	24.9	
SUE_138	0.1	1.8	22.2	67.3	4.5	
SUE_137	0	1.2	8.6	58.8	16.3	
SUE_136	0	1.5	12.5	68.6	12.9	
SUE_135	0	1	8.5	63.6	12.2	
SUE_132	0	0	1.6	57.7	30.7	
DIC_244	1.4	3.1	18.5	69.3	6.4	
DIC_245	0	0	8.6	82.9	8.5	
DIC_246	0	0	8.7	83.5	7.8	
DIC_86	0	2.1	28.4	66	2.6	
DIC_87	0	0	14.6	82.4	3	
DIC_88	0	0	15.4	81.6	3	
(Table 3 Cont.) Sediment Samples	Very Coarse Silt (%)	Coarse Silt (%)	Medium Silt (%)	Fine Silt (%)	Very Fine Silt (%)	Clay (%)
SUE_139	5	1.6	1	1	1	1.4
SUE_138	0.7	0.6	0.5	0.6	0.7	0.9
SUE_137	3.8	2.8	2.4	2.3	1.9	1.9
SUE_136	1.5	0.6	0.5	0.6	0.6	0.8
SUE_135	3.4	2.1	1.6	1.8	1.6	1.8
SUE_132	5.4	1.2	0.7	0.8	0.8	1.1
DIC_244	0.4	0.1	0.1	0.1	0.2	0.4
DIC_245	0	0	0	0	0	0
DIC_246	0	0	0	0	0	0
DIC_86	0.3	0.1	0.1	0.1	0.1	0.2
DIC_87	0	0	0	0	0	0
DIC_88	0	0	0	0	0	0

Table 4: Table displaying the exact percentages of the sand/silt content of each of the samples around Caminada Pass. The first table displays the sand grain sizes from very coarse to very fine sand. The second table describes the silt content from very coarse to fine silt. There is also a column for clay in this table, but the numbers are very small that they do not make much of a difference in the overall content of each sample.

### *Ebb Tidal Delta Volume Results*

Table 5 shows the calculations of the ebb tidal deltas for each timeframe and was derived from the area change bathymetric maps. The highlighted box is the total change for

each timeframe. The 1890's-1930's timeframe had an ebb tidal delta volume change of  $1,459,752.9\text{m}^3$ . The 1930's to 1980's timeframe had an ebb tidal delta volume change of  $1,537,738.2\text{m}^3$ . The 1980's to 2006 had an ebb tidal delta volume change of  $1,760,174\text{m}^3$ . The total delta volume change from 1890's to 2006 was  $5,322,626.7\text{m}^3$ . Miner et al., (2009a) calculated the overall net volume change for the Caminada Pass to be  $7,020,958.31\text{m}^3$ . The overall volume change is  $1,698,331.61\text{m}^3$  less than the calculation from this study.

Ebb Tidal Delta Change			
	Area ( $\text{m}^2$ )	Contour (m)	Total ( $\text{m}^3$ )
1890-1930	1,190,307	1	1,190,307
	90,583	2	181,167
	44,139	2	88,278
			1,459,752
1930-1980	1,143,432	1	1,143,432
	3,105	1	3,105
	79,227	1	19,227
	185,987	2	371,974
			1,537,738
1980-2006	1,905,554	0.5	952,777
	732,268	1	732,268
	37,564	2	75,129
			1,760,174
1890-2006	2,699,345	1	2,699,345
	981,056	2	1,962,113
	217,534	3	652,602
	2,854	3	8,564
			5322626

Table 5: Table displaying the calculations of the ebb tidal delta volume changes for the timeframes 1890's-1930's, 1930's-1980's, 1980's to 2006, and 1890's to 2006. The total volume change is highlighted for each timeframe.

## *Hurricane Impacts*

More than 32 tropical cyclones (Fig. 27) have impacted the Caminada Pass area during the 1890's-2006. There were seven tropical cyclones during 1890's and 1930's. Hurricanes at that time were not named but one of the most notable storms during this time period were the Cheniere Caminada Hurricane (strong category 3) that destroyed Cheniere Caminada plantation and killed 779 people in 1893, the 1909 Hurricane (category 3) that killed 353 people, and the 1915 hurricane (category 3 to 4) that killed 273 people (Stone, 1997). There were 12 tropical cyclones to hit proximal to this area during 1930's-1980's. They included: Hurricane Flossy (Category 1) that completely submerged Grand Isle in 1956; Hurricane Betsy (Strong Category 4) that hit in 1965 where winds were gusting to 100mph and killed 58 people across southeast Louisiana; and Hurricane Camille (Category 5) that hit in 1969. A total of 16 tropical cyclones impacted this area during 1980's-2006. Some of the most notable ones include: Hurricane Juan (Category 2) that hit in 1974 and submerged Grand Isle and killed 12 people; Hurricane Andrew (Category 3) that hit in 1992; and Hurricane Katrina (Category 4) that hit in 2005 that killed 1,697 people and is recorded to be the most costly storm of all time (Fritz et al., 2007).

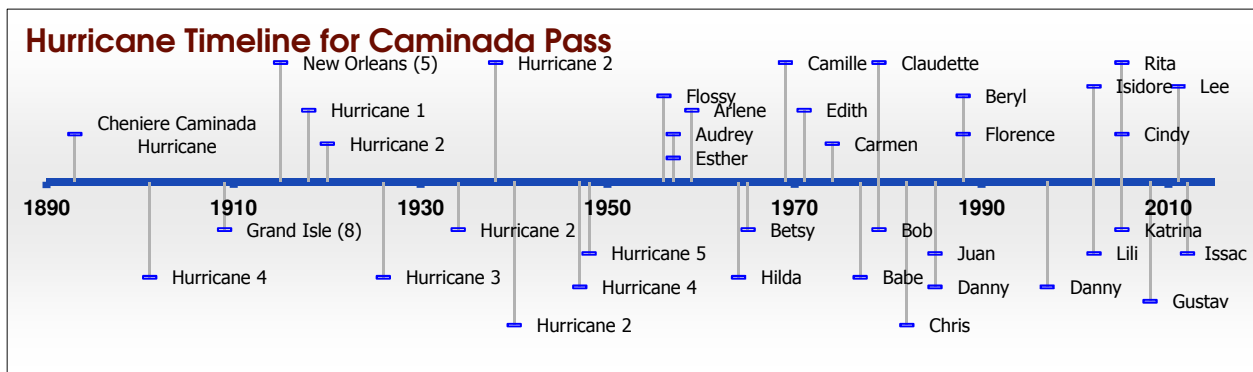


Figure 27: Timeline of all of the hurricanes to impact Louisiana between 1890-2012. There have been a total of 38 hurricanes to affect the region during this time range. Atlantic hurricanes were not named until 1953, so some of the storms prior to this date were numbered and others were named for the areas that were most affected by the storm (Stone et al., 1997).

## Discussion

### *Coastal Evolution of Caminada Pass*

The coastal evolution of Caminada Pass has been split into three categories: long-term changes, mid-term changes, and short-term changes. These ranges provide an opportunity to better understand how observed modifications taking place in and along the pass are a reflection of different processes operating across different timescales. The long-term changes include changes that occurred to Caminada Pass on a multi-decadal scale. The long term changes are broken up into three time periods with each spanning a course of approximately 30 years. The time periods include changes and events that occurred during 1890's-1930's, 1930's-1980's, and 1980's-2006. Mid-term changes include changes that occurred to Caminada Pass on a decadal scale. The time periods are separated by decade beginning with the 1970's and thus covers approximately the last 30 years. Short-term changes include changes to Caminada Pass that have occurred annually within the last 10 to 15 years.

### *Long-term Changes in Caminada Pass*

The long-term evolution of the Caminada Pass tidal inlet spans approximately 120 years from the 1890's to 2006. The long-term growth of Caminada Pass is best illustrated in the cross section plot derived from the bathymetry because it gives a quantitative number how much the channel as widened and deepened as well as any migration that the inlet channel has made during this timeframe. The shoreline trajectories were also used to provide a land water border for the adjacent islands.

### *1890's-1930's*

From the shoreline polygons (Fig. 28), it was determined that Elmer's Island had retreated and moved 377m and the west end of Grand Isle has retreated 870m to the northeast between 1890's and 1920's. The total volume of the ebb tidal delta was  $1,459,752.9\text{m}^3$  and had migrated toward the east as indicated by area change maps during this time frame. As indicated from the bathymetry during the time periods 1890's- 1930's, the west end of Grand Isle had been severely eroded due to all of the sediment being transported to the eastern end of Grand Isle due to longshore transport. The main difference in appearance from the 1890's western end of Grand Isle and the 1930's western end of Grand Isle is that the narrow terminal end of Grand Isle extended into Caminada Pass toward the northwest in the 1930's instead of toward the west in the 1890's. The flanking barrier spit from Elmer's island had also been eroded. The overall change between these two time periods shows little change to the growth of the inlet due to a smaller tidal prism, but the adjacent islands displayed multiple changes due to the instability of the sediment budget and lateral movement of the island.

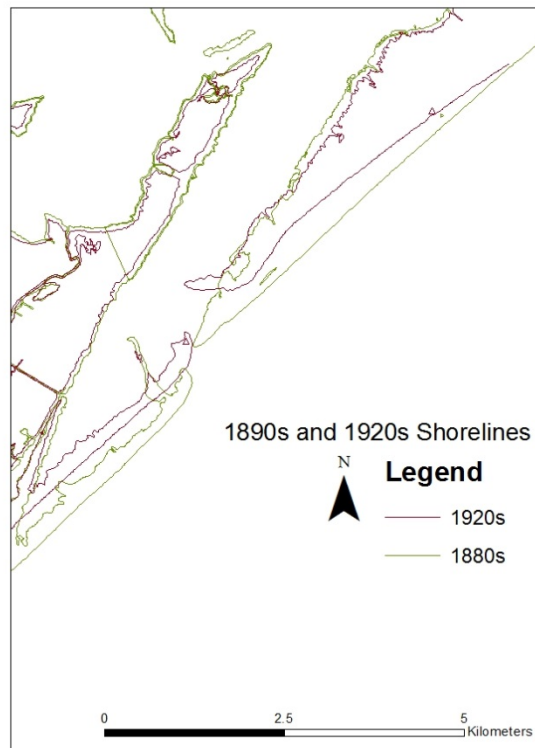


Figure 28: Map displaying the distribution of the 1890's and 1920s shorelines in the area. There have been lateral movements occurring in this area between the two time periods as a result of coastal land retreat and longshore transport (Martinez et al., 2009).

### *1930's to 1980's*

Bathymetric data indicates that spit growth toward the north from the gulf-facing side of Elmer's Island occurred during this time period, as opposed to the data from the 1930's when spit growth was noticeably absent. Due to the placement of the rock jetty at Caminada Pass and an increase in tidal prism which caused an increase of the ebb tidal delta ( $1,537,738.2\text{m}^3$ ), sediment succumbed to tidal currents and was deposited along the Caminada headland spit. The western end of Grand Isle spit was no longer toward the north. The Caminada Jetty also stabilized Grand Isle, and in turn, the western end of Grand Isle was thicker and had extended toward the west.



### *1980's-2006*

The west end of Grand Isle was relatively stable with no discernible significant erosion or deposition evident in the available datasets especially during the last decade. The inlet continued to increase by widening and deepening. The ebb tidal delta increased to 1,760,174m<sup>3</sup>. During this timeframe, there was an increase in the spit length off the Caminada Headland due to the same combined impacts of reduced sediment bypassing around the ebb tidal delta, and an increase in tidal prism causing faster tidal currents (exceed 1 m/s peak ebb discharge)(Howe, 2009) through the inlet, which transport sediment into the backbarrier where is subjected to waves, and since the maximum currents are confined entirely to the western thalweg (Howes, 2009), deposited onto the Elmer's Island spit in the form of a recurved spit.

Sediment bypassing processes is essential for the transport of sediment across inlets. Studies show that bypassing transport volumes can vary depending on setting from 10-30% (FitzGerald, 1988) of the longshore transport rates. There are no studies addressing sediment bypassing at Caminada Pass, but the depth of the distal ebb delta, may prohibit this process or limit to a lower percentage. Ebb tidal deltas represent a fraction of the coastal budget, but can affect an area locally (FitzGerald, 1988); therefore, Sediment bypassing may further contribute to the downdrift coastal budget on Grand Isle, and perhaps is the reason why the shoreline immediately after the east jetty is eroding.

### *Mid-term Changes in Caminada Pass*

#### *1970's*

Changes to the inlet were also documented using true color satellite Landsat TM images between 1972 and 2010. The first images available are from 1972(Fig. 29), approximately the time of completion of the rock jetty on the western end of Grand Isle. Hurricane Edith had hit the year

before, and Caminada Pass was in a state of recovery at this time. Elmer's island had a narrow beach-dune system and spit accretion was taking place toward the north into Caminada Pass. Overwash fans, along the narrow headland were discontinuous. Most of the accretion occurred along the easternmost end of the island, along what is referred to as a pivot point on Elmer's Island, a transitional zone where the beach merges into a northerly trending spit that extends along the margin of Caminada Pass. The west end of Grand Isle was also narrow on the gulfside of the island and thickest toward the terminal end. Through the 1970's, with the exception of 1974, 1977, and 1979, there was a steady increase in length of the Elmer's Island spit (Fig. 39). Hurricane Carmen, Babe, and Claudette led to a fragmented spit and near absence of beaches. The interpretation presented herein is the construction of the 1972 jetty likely also contributed to an interruption of the longshore transport patterns toward the east and the corresponding development of an erosional shadow on the downdrift side of the inlet. More of the sediment was then subject to flood and ebb tides and deposited along the Elmer's island spit or transported offshore in the ebb tidal delta.

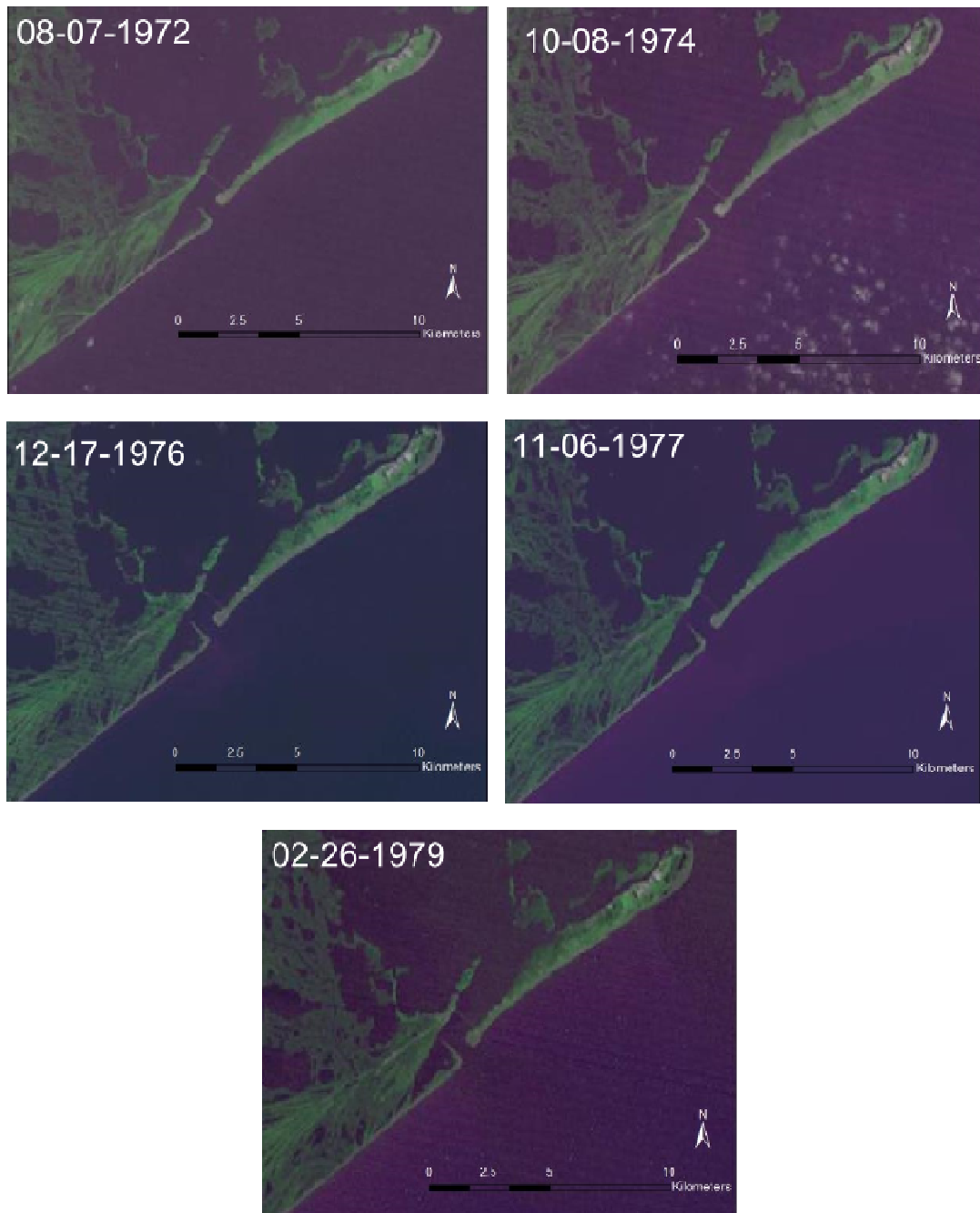


Figure 29: Landsat satellite Images of Caminada Pass during 1972, 1974, 1976, 1977, and 1979. These images document the sequential growth of the Elmer's island spit in the 1970s. Most of the accretion of the Elmer's island spit occurred along the pivot point. The interpretation presented herein is the rock jetty placed on the western end of Grand Isle is responsible for the increase in length of the Elmer's island spit because the jetty disrupted littoral drift causing more of the sediment to be transported and deposited during the ebb and flood tides.

### *1980's*

During the 1980's (Fig. 30), the same general process continued to occur along Caminada Pass. The Elmer's island spit continued to grow in length and accretion along its pivot point was documented in 1981 Landsat image (Fig.30). In 1982, Hurricane Chris however eroded away the previously deposited sediment, and vegetated overwash platforms also appear for the first time in Landsat images of the Elmer's island backbarrier. Hurricane Juan contributed to erosion of the previously deposited sediment along the Elmer's Island pivot point again in 1985. After this storm event, accretion around the pivot point increased in length causing the spit to extend toward the north. The west end rock jetty was extended in 1987 further contributing to the increase of the Elmer's Island spit and the stability of Grand Isle. Through the 1980's, the west end of Grand Isle showed continued accretion on its terminal end in the backbarrier.

### *1990's*

At the beginning of the 1990's (Fig. 31), relative to earlier time periods, the Elmer's island spit was no longer a narrow sandy flank of land, but attained a true beach with vegetated overwash platforms and an increase in width thickness along the pivot point and previously deposited sediment on the east side of the spit. The 1990's were a prime example of the spit accretion process that occurred in Caminada Pass, because it was a quiet decade in terms of hurricane impacts. The only hurricanes to impact to the area were Hurricane Andrew in 1992 and Hurricane Georges in 1997. The images from these years show erosion of the pivot point on Elmer's island, but the inlet parallel beach maintained the general geometry that had developed in previous time frames. An example of this coastal process can be seen as is evident in figure 32.

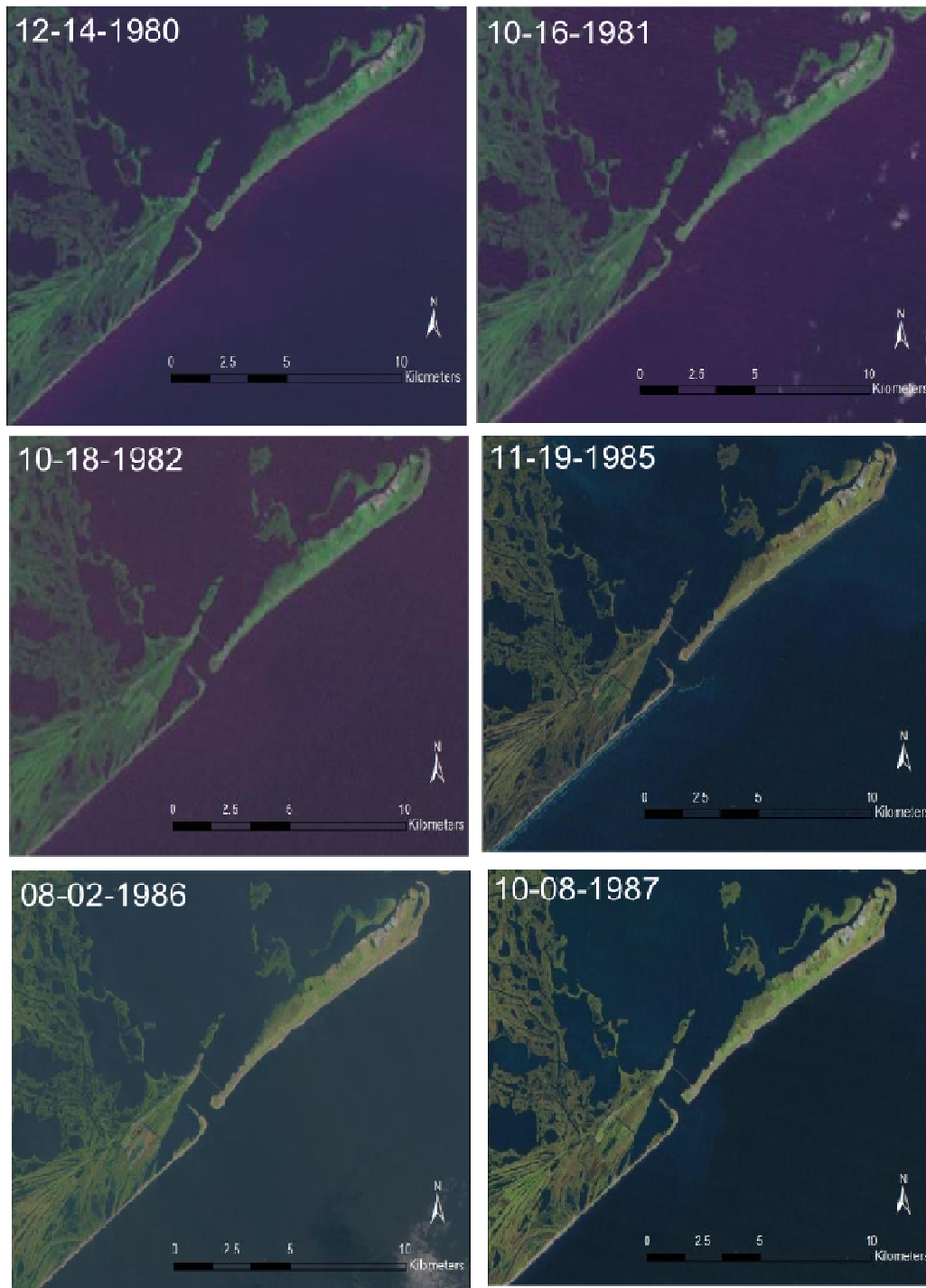


Figure 30: Landsat satellite Images of Caminada Pass during 1980, 1981, 1982, 1985, 1986, and 1987. These images document the continued growth of the Elmer's island spit, which was initiated in the 1970's when Hurricanes Chris and Juan that hit in 1982 and 1985, respectively, contributed to the modification of the spit by eroding the sediment along the inlet parallel beach and pivot point off Elmer's island in those years. The spit recovered from these storms and continued to grow in length toward the north in subsequent years.

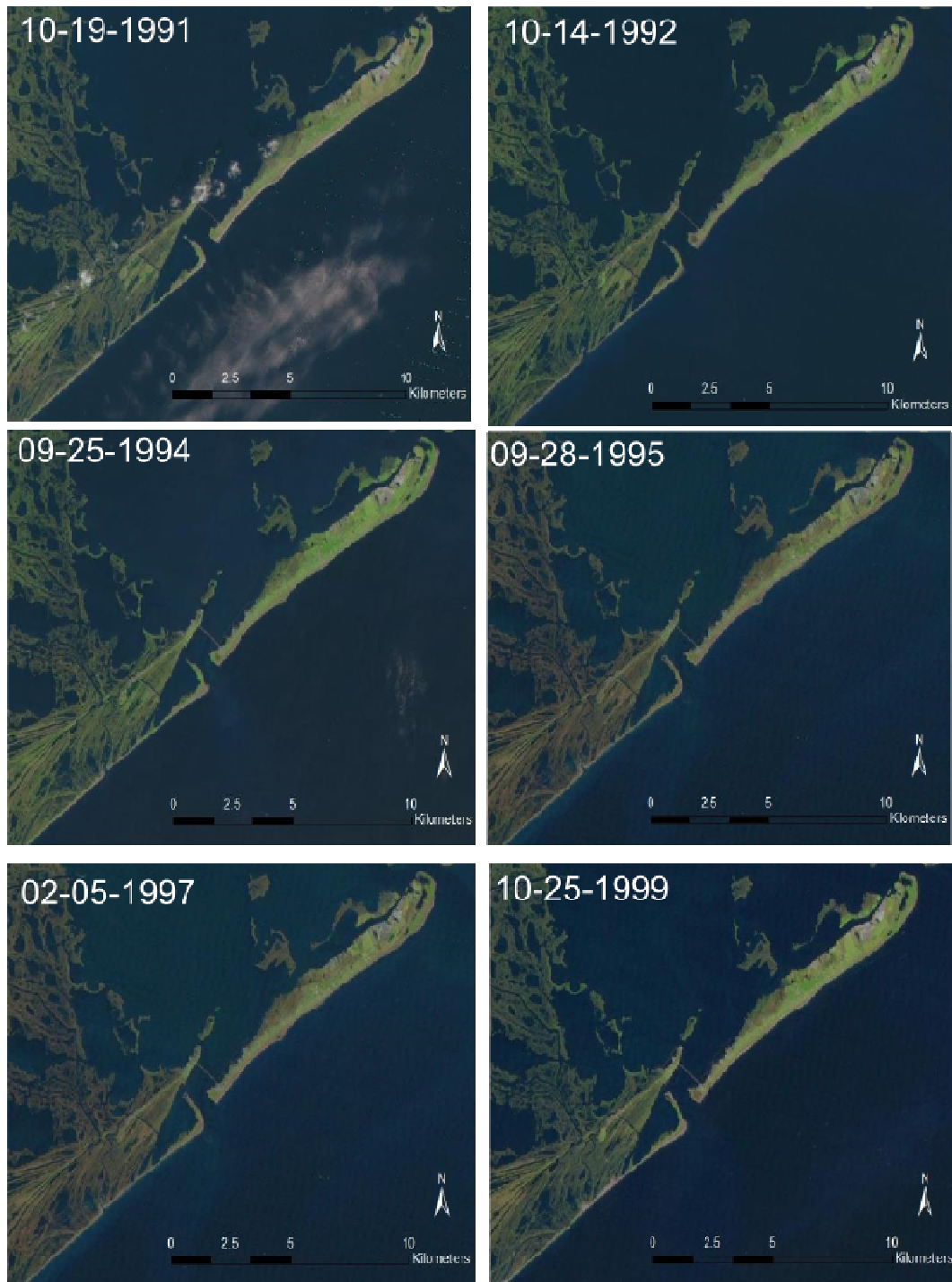


Figure 31: Landsat satellite Images of Caminada Pass during the 1990, 1992, 1994, 1995, 1997, and 1999. During the 1990s, the spit grew from a sandy flank of land to a true beach with vegetated overwash and an increase in width thickness. This decade represented, compared to the previous decades, a relatively quiescent period of hurricane activity and thus provides a good time frame to analyze the morphologic changes of the beach spit system along the eastern end of Elmer's island

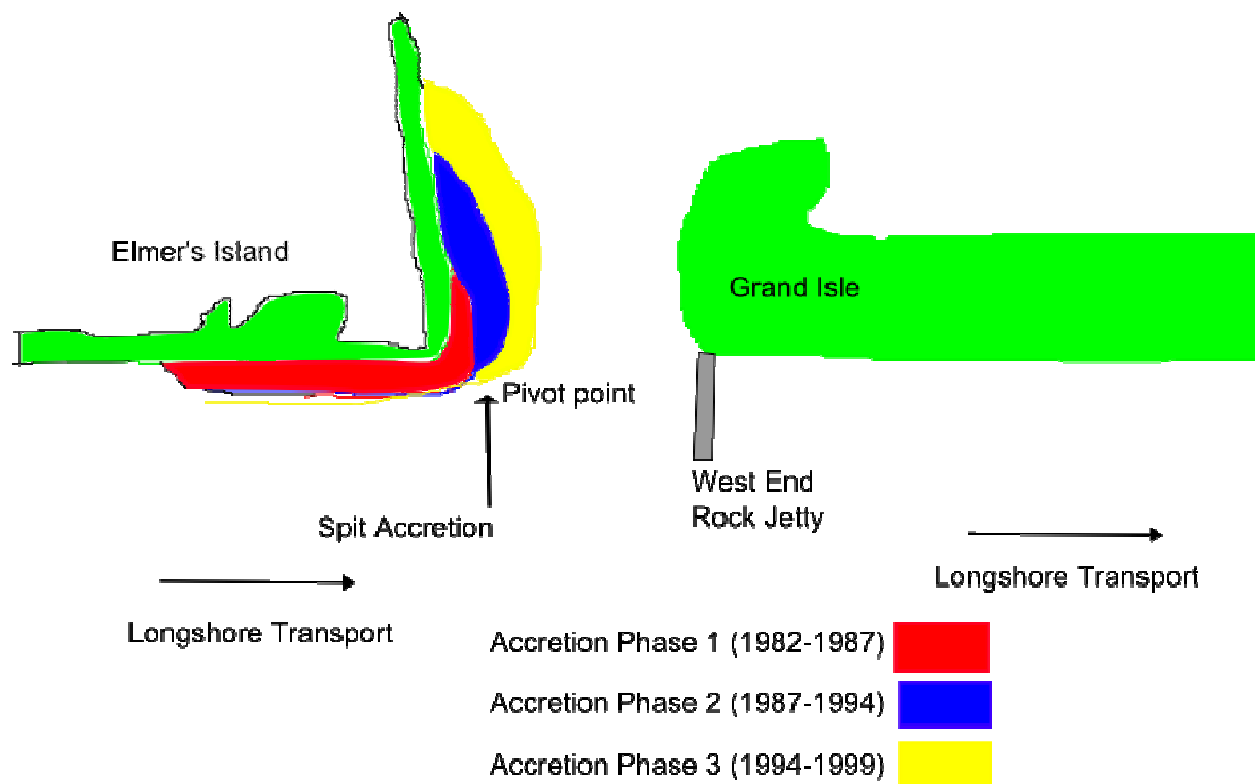


Figure 32: Diagram illustrating Caminada Pass spit growth, tidal exchange and off Elmer's Island. Longshore transport sediment toward the east where it is subjected by the jetty and reduced sediment bypassing due to the ebb tidal delta (not shown). Sediment carried along Elmer's Island gets deposited at the end of Elmer's Island where the spit pivots toward the north into Caminada Pass. The accretions continue to increase along the pivot point and into the inlet in the form of finger-like strand plains. It continues to build expanding onto Elmer's Island spit. Grand Isle retained a stays relatively stable configuration during this time period.

### 2000's

During the 2000's (Fig. 33), changes started to occur along the spit. The spit reached its northward extent into the backbarrier extension of the Caminada headland ridges. The spit began to prograde toward the northeast following the Cheniere Caminada Coastline. It is herein suggested the spit starting following the tidal current in the pass. The spit also began to thin except toward the terminal end where most of the accretion was taking place. Hurricanes Katrina and Rita hit in 2005 and caused significant impact along Caminada Pass. Due to the storms, a significant sized breach,

that was 400m in length, developed on the Elmer's island headland. Grand Isle, which had remained relatively stable, shrank in size. The Elmer's island spit also shrank significantly in size

In 2007 imagery, the breach was still present along Elmer's Island and there is some indication of tidal flow into this breach because of sediment is prograding from the breach toward the north. There was still continued accretion along the terminal end of the Elmer's Island spit, which having reached its northeastern extent, started accreting more toward the east. Tidal prism changed to accommodate the breach sending more of the sediment into the backbarrier in the spit and increased movement of sand toward the Grand Isle Bridge. By the beginning of 2008, the breach had nearly closed up due to longshore transport, but Hurricane Gustav hit that same year and opened up another breach along the inlet parallel beach off the Elmer's Island spit changing tidal prism again to accommodate for the new breach. This breach was 184.3m in length. The breach in the middle of the spit continued to increase in size as the terminal end of the spit continued to accrete toward the east/northeast. By 2010, the spit had grown to 388m and the inlet parallel breach accretion at the end of the spit had reached the Grand Isle Bridge. Tidal exchange was no longer occurring on the backside of the Elmer's Island inlet parallel beach causing the sediment to merge with Cheniere Caminada.



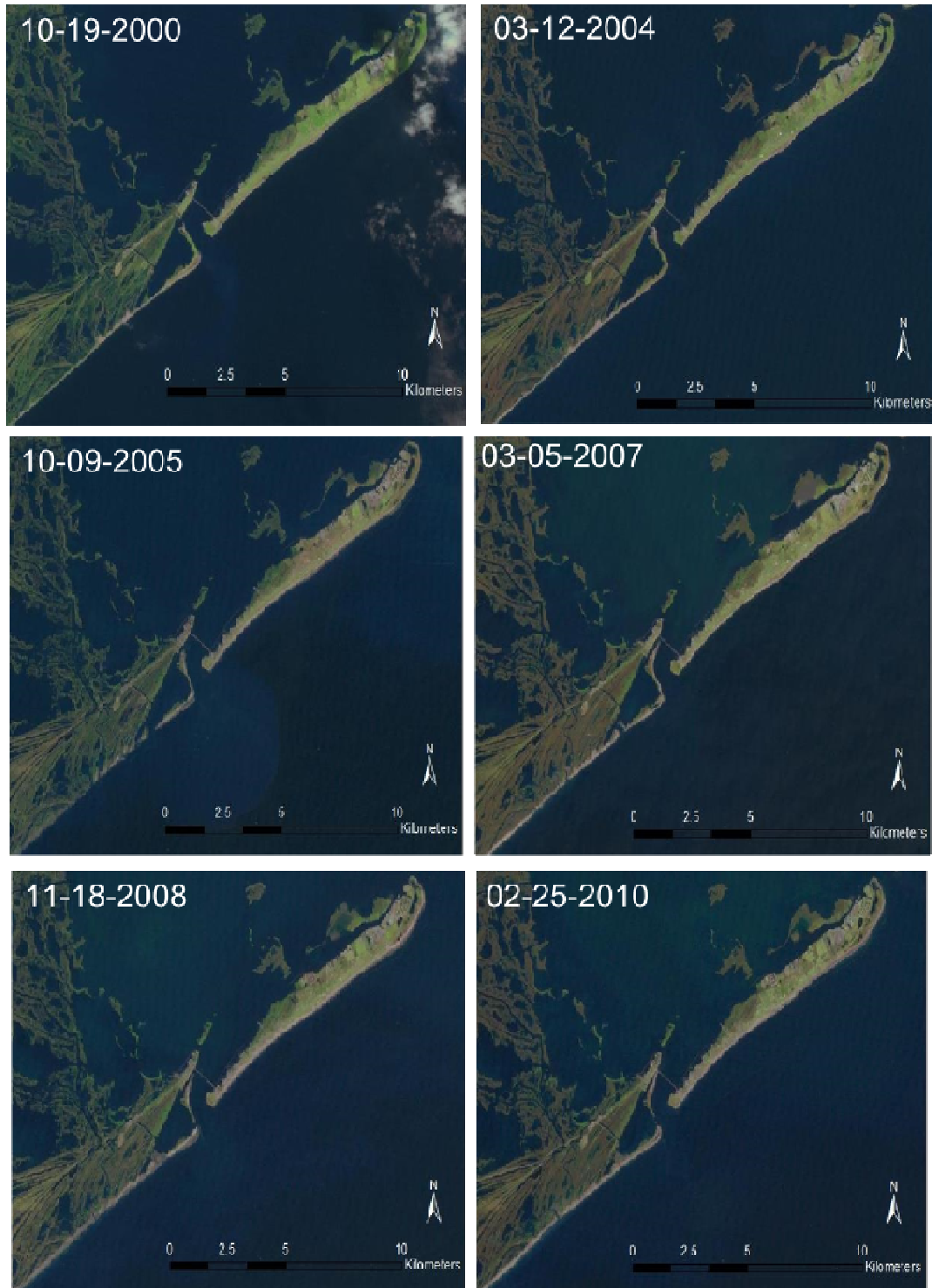


Figure 33: Caminada Pass in Landsat images during the 2000, 2004, 2005, 2007, 2008, and 2010. Caminada Pass underwent many modifications during this decade due to multiple storms passing through this area as well as a change in the vector of spit accretion. The spit started to accrete toward the northeast in 2004. The spit was also breached in 2008 due to Hurricane Gustav resulting in a separation of the spit from Elmer's Island mainland.

## *Short-term Changes*

### *Anthropogenic changes to Caminada Pass*

Caminada Pass has undergone many anthropogenic projects to keep the tidal inlet, Grand Isle and the Caminada-Moreau headland stabilized. Historical construction projects on Grand Isle include: the placement of the rock jetty on the west end of Grand Isle (1971) dune/beach nourishment (1984, 1991, 2005), the Town Rock Project (breakwaters and groin systems, 1989), the sand grabber demonstration project (1994) and detached breakwaters (1995, 1999). These man-made structures were built to provide protection to Grand Isle and Elmer's Island from coastal erosion and storms(USACE, 2012).

Two of the more recent projects include: the Grand Isle and Vicinity Project and The Barataria Basin Shoreline Restoration Project. The Grand Isle and Vicinity project consisted of a linear 2,438m dune built along the gulf side of Grand Isle, as well as repair all breakwaters and jetties. This construction project was created to repair damages done to the island from Hurricanes Katrina and Rita in 2005. The sand dune "burrito" project was delayed in September 2008, due to Hurricane Gustav, but was completed in December 2008. A geotextile tube core filled with sand that is 9,449m in length has been built to reconstruct the dunes that were built after Hurricane Katrina. This geotextile tube was used to make the sand dune structurally sound and to keep the sand within the tube from blowing away (USACE, 2008).

The Barataria Basin Shoreline Restoration project is one component of the recent Louisiana Coastal Master Plan 2012. The project proposed is set to re-establish the Elmer's Island shoreline by providing 420 acres of barrier headland with the building of beach, dune, and back-barrier marsh system. The project will reduce erosion of adjacent marshes, close existing breaches, prevent

further breaches, and introduce dune vegetation to the area. A possible borrow site for this project is Caminada Pass (USACE, 2012).

### *Impacts of recent hurricanes*

The short term impacts along eastern end the Caminada-Moreau headland and Grand Isle can be attributed to transgressive processes that are greatly increased by the effects of events such as hurricanes. The following photo pairs were taken in 2005, 2007, 2008, and 2012. The 2005 photos were taken post Katrina, the 2008 photos were taken post Gustav, and the 2012 photos were taken post Isaac. The 2007 photos were taken during a year when no hurricanes made landfall and provide a good example of the recovery response of the barrier islands, and how they look during a normal year.

The first sets of photo pairs (Fig. 34) were taken from the same general angle of the west end of Grand Isle toward the northeast, which is indicated by the yellow arrow. The images that are compared to one another are 467(2005), 1915(2007), 425,428(2008), and 3451(2012). In the 2005 photo, the west end of Grand Isle retains its general drumstick shape, but the vegetation is mostly dead. This is evident since the vegetation is mostly brown in the 2005 photo and green in the 2007 photo. The 2007 photos display distinctive beaches that are thickest adjacent to the jetty and thin toward the east. In the 2005 photo, the beach is absent since the sand was stripped from the beach and formed subaqueous sandbars. The waves are coming in from the same general direction from southeast to northwest. The gap between the jetty and Grand Isle is completely filled with water in the 2005 picture and contains small sandbars in the 2007 picture. The inlet parallel beach of Elmer's Island can be seen toward the back of Caminada Pass in both photos. The purple arrow indicates the progradation of the inlet parallel beach in all four photos. The 2007 photos display how much the inlet parallel beach has grown over the course of two years. Traces of the

inlet parallel beach can be seen approaching the bridge in the 2007 photo, as opposed to the 2005 photo, where the outward extent of the inlet parallel beach hasn't even reached the camps.

When the 2007 photo is compared to Image 425 (post Gustav, 2008), major changes are evident. These photos were taken one year apart, and it provides a really good example of how much impact a hurricane can have on a barrier island. In the 2008 photo, the beach has been completely stripped away, and the only evidence of its existence, is in the shape of subaqueous sandbars. Grand Isle retains its same uniform shape because the vegetation holding it in place. There is also a much larger gap between the jetty and the island. The sand that is shown in the gap in the 2007 photo is no longer there in the 2008 photo. The inlet parallel beach off Elmer's Island is not shown in this picture, but can be seen in Image 428. The inlet parallel beach has retracted toward the west due to Hurricane Gustav as illustrated by the purple arrow. Where the outward extent of the inlet parallel beach was clearly evident in the 2007 photo, the 2008 photo displays it discontinuous and barely reaching the center of Cheniere Caminada.

The final comparison of the area is observed in Image 3451. The island itself is much smaller than compared to the other photos, and it seems to be straightening out its drumstick shape on the pass side. The gap between the rock jetty and Grand Isle is still visible, but unlike the 2008 photo, the gap is filled with subaqueous sand bars. The rock jetty also looks to be partially submerged in the 2012 photo. The beach on Grand Isle is also absent in 2012 photo leaving only the vegetation line visible on the gulfside of the island. The inlet parallel beach has prograded to the eastern side of the Grand Isle Bridge, and there is vegetation beginning to grow on the western end of it. The docks stretching out from the homes on Cheniere Caminada are now ending on a beach, when it once ended in water.

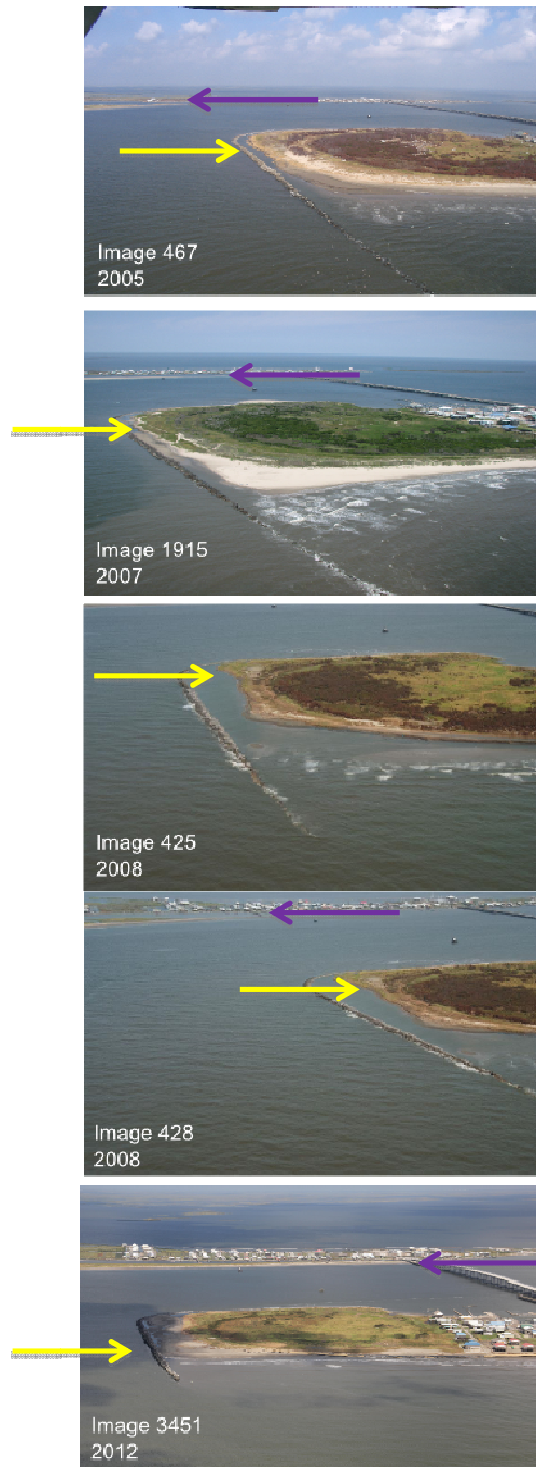


Figure 34: Oblique aerial photo images 467, 1915, 425, 428, and 3451 showing the west end of Grand Isle from 2005, 2007, 2008, and 2012. These photos provide examples this shoreline stretch before and after recent hurricanes that have hit southeast Louisiana. Notable changes include the absence of a beach in the post storm pictures and the growth of the inlet parallel beach off Elmer's Island. The yellow arrow indicates the changes made to the western end of Grand Isle and the purple arrow displays the progradation of the inlet Parallel beach off the Elmer's Island spit.

The next set of photo pairs (Fig. 35) is of the east end of Elmer's island in the direction from east to west and is indicated by the orange arrow. The images used are 468 and 469(2005), 1902(2007), and 3650(2012). In the 2005 photo, Elmer's island is discontinuous and the beach is absent. The orange arrow illustrates the subaqueous sandbars where the beach is supposed to be in the 2005 photo. This is evident due to the distinctive sandy beaches visible in the 2007 photo in the same location, and the waves breaking around the sandbars in the 2005 photo in the same general direction as the waves breaking around the beach in the 2007 photo. The vegetation is also nearly absent on the bayside of the island toward the beginning of the pass in the 2005 photo. The 2007 photo clearly shows vegetated overwash on the bay side of the island. The other noted comparison between the two pictures is that the breach has almost closed up in the 2007 photo as illustrated by the green arrow. There is a small pool of water still located on Elmer's Island in the 2007 photo, but it completely surrounded by beach and vegetation. The exact location of the breach can be determined due to the triangular shaped vegetated overwash that is visible in both pictures as indicated by the green arrow.

There was no photo taken in 2008 of this particular area, so this year will be omitted in this photo comparison. The 2012 photos show the impacts of Hurricane Isaac. The beach around the pivot point of the Elmer's Island headland as it turns into Caminada Pass is absent. There is just a narrow stretch of sand with vegetated overwash in the backbarrier in the 2012 photos as opposed to the wide spread expanse of sand in the 2007 photo. Elmer's island is still breached in the same location in both photos, but the sand is more widespread in the backbarrier in the 2012 photo than in the 2007 photo.

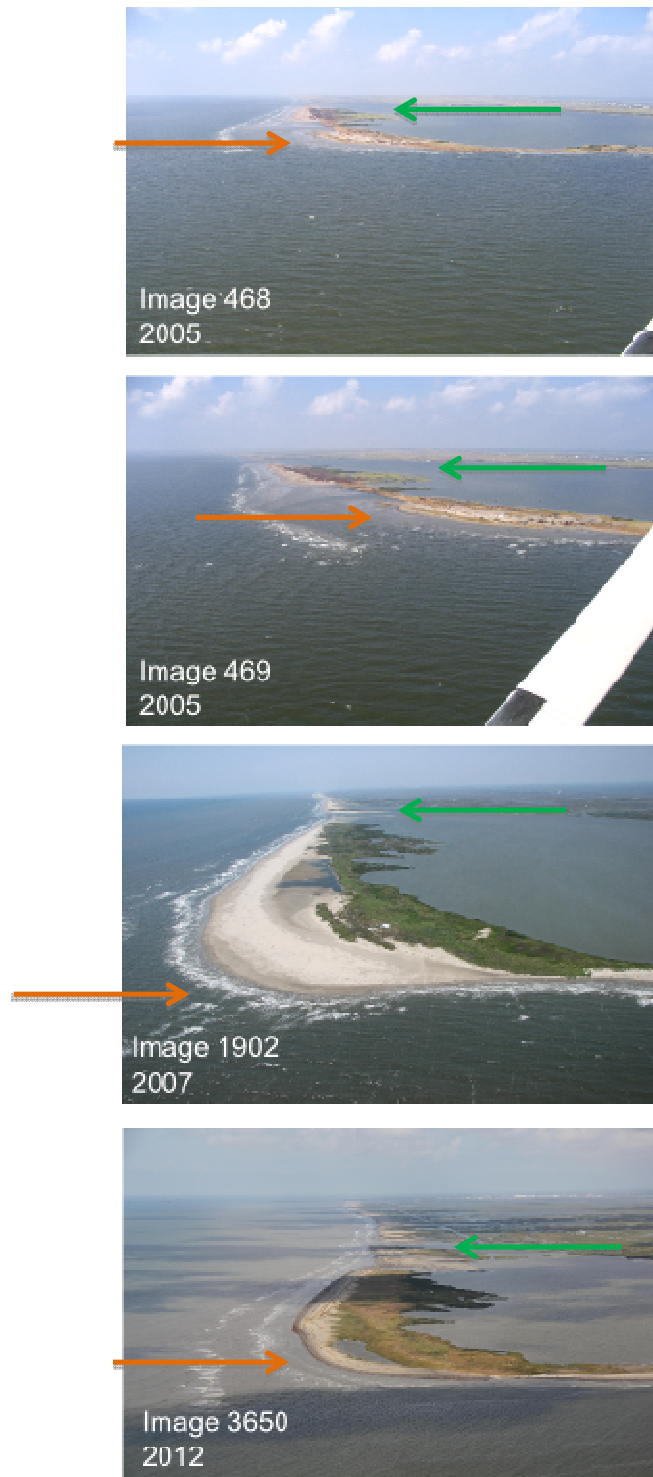


Figure 35: Oblique aerial images 468, 469, 1902, and 3650 showing the east end of Elmer's Island. These photos provide examples of this shoreline stretch before and after recent hurricanes that have hit southeast Louisiana. Notable changes include the changes to the breach in the photos and the changes that have occurred along the gulfside beach. The orange arrow displays the changes to the beach on the gulfside of Elmer's Island, and the green arrow indicates the breach that was created during Hurricanes Katrina and Rita.

The next group of photo pairs (Fig. 36) includes: image 470 (2005), image 1899 (2007), image 1898 (2007), image 440 (2008), image 438 (2008), and image 3728 (2012). These photos display the inlet-parallel beach off the end of Elmer's Island in the direction toward the northeast. In the 2005 photo, the Caminada headland, which is indicated by the orange arrow, had a narrow beach that increased in size as the island moved toward the eastern end of the island. There is little vegetation in the area and the waves are hitting the island at an oblique angle toward the northeast. There are also visible subaqueous sandbars that provide an indication of the foreshore expanse of the beach prior to the storm. The photo from 2007, however, displays a wide beach with an almost as equal wide expanse of vegetation that is exposed in the backbarrier. As the spit turns toward the northeast into Caminada pass, the 2005 photo shows a linear stretch of beach that is backed by overwash, and it thickens toward the northeast at the terminal end of the of the inlet parallel beach. The terminal end is indicated by the purple arrow. The 2007 photo shows the sandy beach in a hummocky formation, which is indicated by the red arrow, with vegetation backing it into Caminada Bay. The inlet parallel extends further toward the west than the 2005 photo.

The 2008 photos display the Elmer's island spit in two different photos. Image 440 shows the gulfside of the spit as it turns into Caminada Pass. Image 438 shows a continuation of 440, and its viewpoint focuses on the inlet parallel beach and Cheniere Caminada. This photo is different from the 2007 photos because the sandy beach is absent with the exception of some small subaqueous sandbars indicating where the beach used to be. There is also a breach, which is indicated by the blue arrow, of the spit that was created due to Hurricane Gustav.

Compared to the 2012 photos, the 2008 inlet parallel beach was a little less stable under the pressure of a hurricane than it was when Hurricane Isaac hit in 2012. The gulfside sandy beach is still mostly eroded away, and subaqueous sand bars are still outlining the area where the beach used to be, but the hummocky formation that the spit created in Caminada Pass is still noticeable.



The island was breached during Isaac, and some of the vegetation is absent south of the breach. The sandy beach appears to be absent on the northern part of the breach, but it looks to be stable because the spit stretches out passed the frame of the photo toward the northeast.



Figure 36: Oblique aerial photos showing the extended Elmer's island spit from the years 2005, 2007, 2008, and 2012. The photo is from the viewpoint toward the northeast. The photos show before and after shots of the pass after it had been hit by major storms. Notable changes include the growth of the inlet parallel beach and the breaches that have happened due to the recent hurricanes. The purple arrow represents the terminal end of the inlet parallel beach off the Caminada Headland. The orange arrow represents eastern end of the Caminada Headland. The blue arrow displays the location of the breach that developed during Hurricane Gustav. The red arrow illustrates the hummocky curvature of the inlet parallel beach.

## Conclusion

1. *What has been the geomorphic framework of Caminada Pass's evolution during historic times, namely between the 1880s and 2012? Specifically, how has the inlet expanded in width or depth and are there any specific changes to the inlet geometry that are a result of nearby natural or anthropogenic shoreline alterations.*

Successive bathymetric surveys indicate that Caminada pass has quadrupled in cross-sectional area from 1880 to 2006 in terms of cross-sectional growth. Caminada pass had a cross-sectional area of 809m<sup>2</sup> in 1880, 1,353 m<sup>2</sup> in 1930, 1,532m<sup>2</sup> in 1980, and 3,372m<sup>2</sup> in 2006 (FitzGerald, 2007).

During the 1890's, the inlet was relatively small with an average -3.4m depth relative to MSL in the inlet throat and 350m in length. The sediment source was from the Caminada-Moreau Headland west of Caminada Pass and most of the sediment was transported to the eastern end of Grand Isle causing the sediment starvation and instability of the western side. During the 1930's, the pass migrated toward east and the adjacent islands to the northeast due to longshore transport from the west. The inlet increased in depth by 0.6m and, and increased in length by 75m from the 1880's. The inlet change was gradual most likely due to the tidal prism not being as large as it is today.

Between the 1930-1980s, the inlet was subjected to modification, with the placement of a rock jetty on the west end of Grand Isle in 1972. The placement of the jetty affected the adjacent shoreline. For example, shortly after the construction of the jetty, the western end of Grand Isle appeared to have become stabilized because it increased in size in the backbarrier along the pass, likely also, at least temporarily stabilizing the inlet channel location. Downdrift of the jetty however erosion took place, whereas on the updrift side, the Elmer's Island spit prograded into Caminada

Bay. Hurricanes, in the 70s and 80s, affected Elmer's Island spit by disrupting growth of the Elmer's Island spit, as indicated by an examination of the Landsat images. The inlet grew 1.1m in depth and expanded 175m in width.

Between the 1980's to 2006, the inlet increased by an average of 2.8m in depth and 75m in width. During this time period, the inlet underwent the most changes along the Elmer's island spit. During the 1990s, growth of the spit continued since it was a relatively quiescent period of hurricane activity with only a limited number of tropical cyclones passing across nearby the Louisiana coast. As longshore transport moved sediment toward the east, sediment was deposited at the eastern end of Elmer's island along the pivot point and into Caminada Pass toward the north. Eventually, the inlet parallel beach reached its northward extent in the backbarrier extension of the Caminada headland ridges and began extending toward the northeast in 2004. Elmer's Island was heavily impacted by the Hurricanes of 2005 and 2008 (documented by satellite images and aerial imagery) and created breaches in Elmer's Island in 2005 and the inlet parallel beach in 2008. This event resulted in a drastic change to the vectors of tidal exchange. The spit eventually merged with Cheniere Caminada because the tidal exchange stopped in this area and tidal exchange was diverted to the breach of Elmer's island. The net result was that the original tidal passage closed completely and as a result tidal exchange from part of the backbarrier is now through the hurricane-created breach.

2. *Have the dynamics of the historic changes of Caminada Pass had any specific influences on the ebb and flood tidal deltas?*

An examination of the available bathymetric datasets reveals that the ebb tidal delta has grown during the years due to the increase in tidal prism in the tidal inlet. The ebb tidal delta migrated toward the east during the 1880's to 1930's due to the instability of Grand Isle, and the

volume was  $1,459,752\text{m}^3$ . The west end of Grand Isle was unstable due to sediment transported via longshore transport from the Caminada-Moreau headland and deposited along the east end of Grand Isle causing erosion on the west end. This migration caused sediment reserved in the ebb tidal delta to be lost to Grand Isle or transported to an offshore location. During the 1930's to the 1980's, the ebb tidal migrated back to its original position with the placement of the jetty on the west end of Grand isle. The size of the ebb tidal reservoir grew to  $1,537,738\text{m}^3$  during this timeframe. During the 1980's to 2006, the size of the ebb tidal reservoir grew to  $1,760,174\text{m}^3$ , suggesting limited sediment loss for this time period. Overall the ebb tidal delta increased significantly from 1890 to 2006 with an overall increase of  $5,322,626\text{m}^3$ .

3. *What is the source of sand that, within approximately the last decade, has been deposited on the bayside of the inlet near its entrance to Barataria Bay?*

The source of sand located in the backbarrier region of Elmer's island in Caminada Pass fundamentally derives from sediment of the Caminada-Moreau Headland and is being transported by longshore transport and deposited along the Elmer's Island spit due to tidal exchange ( $0.407\text{m}$  tidal range)(Howes, 2007) within Caminada Pass.  $306.78 \times 10^9\text{m}^3$ (Miner et al., 2009) has been eroded from the Caminada-Moreau headland since 1880 The sediment eroding off of the Caminada-Moreau is transported along the pivot point of the Elmer's Island spit where it is deposited on the inlet parallel beach due to the combined effects of reduced sediment bypassing a tidal currents on the western thalweg (Howes, 2009). Continued accretion of the spit had prograded toward the north until it reached its maximum threshold Once the threshold of the sediment had been reached and it no longer continued its route north, due to interception with Cheniere Caminada, tidal exchange began to transport the sand toward

the northeast. The widening of the spit began to only accrete at the ends as opposed to accreting around the pivot point. With hurricane seasons of 2005, 2008 and 2012, there was a change in tidal exchange causing the end of the spit to eventually merge with Cheniere Caminada due to breaching along the inlet parallel beach. The breach within the spit still continues to affect the tidal exchange and it is currently increasing in size.

4. *What coastal processes or shoreline modifications are controlling or altering the sediment budget of the inlet and the adjacent shoreline?*

The coastal processes that have the most effects on the sediment budget include: longshore transport, cross-shore transport, sediment bypassing, tidal and wave energy, cold fronts and tropical storms, relative sea-level rise, and subsidence. Sediment transported from the Caminada-Moreau headland by longshore transport is suspected to the combined effects of increased tidal exchange, the construction of a jetty on the western end of Grand Isle, reduced sediment transport.

This sediment transported by longshore transport has tidal exchanges with Caminada Pass and some of it is transported to the ebb tidal delta. Most of the sediment is lost to offshore environments, but some comes along shore in the form of washover deposits and is forming the recurved spit off Elmer's Island. Ever since the placement of the jetty at the west end of Grand Isle, there has been an increase of sand transported into Caminada Pass and along the Elmer's Island spit. The jetty has also kept the west end of Grand Isle relatively stable because the terminal end of the western end of Grand Isle increased in size in the backbarrier and held the western end in the same general area. Another process affecting longshore transport is the role of reduced sediment bypassing due to the distal edge of the ebb tidal delta disrupting sediment

transport. Moreover, tropical storms that come through the area cause the beach face along the west end to decrease in size, but eventually the area is built again.

### *Summary*

A better understanding of tidal inlet morphology and evolution can aid in the protection and preservation of barrier islands. Coastal processes surrounding inlets need to be better understood in order to maintain the inlet and the islands effectively. Restoration projects are currently underway to renourish and manage the Louisiana barrier islands, but priorities should be placed on the following suggestions. The tidal prism should be reduced so sediment is not lost to the ebb tidal delta and the inlet throat can reduce in size. Quantifying the sediment budget for all inlets and keeping them updated can aid in keeping track of how and where the sediment is being transported. Man-made sediment bypassing features could also be added so the sediment is deposited along the beach and not in unwanted areas such as the ebb tidal deltas. The ebb tidal delta can also be used for dredging projects to replenish other areas that are in need of sediment. More research should be done on Caminada Pass to give an updated summary of its current location and depth for the present.

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## Appendix- Aerial Photographs

*Oblique aerial photographs taken in 2005*





*Oblique aerial photographs taken in 2007*





Image 1914



Image 1913



Image 1912

















*Oblique aerial photographs taken in 2008 Post Gustav*







*Oblique aerial photographs taken in 2012 post Isaac*



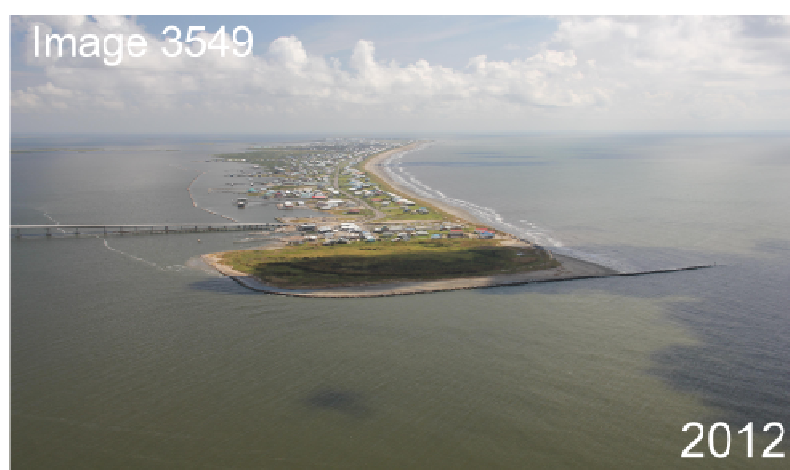




Image 3643



2012

Image 3728



2012

Image 3735



2012

*Recent photographs of Caminada Pass in 2013*









## Vita

Jordyn Ashley Spizale was born in Baton Rouge, Louisiana on September 25th, but grew up in Lockport, Louisiana. Upon graduation from Central Lafourche High School in 2005, she attended Louisiana State University, where she graduated in 2009 with a Bachelor of Science degree in Geology. Jordyn began her Master's Degree at the University of New Orleans in August of 2010 in the Earth and Environmental Science program.